


"The mechanics of Newton, like the geometry of Euclid, was based upon our normal intuitions and it is, therefore, intelligible in the normal sense of the word, just as Euclid is intelligible."

"Einstein has given us signs in the heavens to corroborate his theory and mankind will never go back on signs in the heavens."

A Debate on The Theory of Relativity

WITH AN INTRODUCTION
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THE OCCASION

The debate on relativity contained in this volume was held at Indiana University on May 21 and 22, 1926, under the auspices of the Indiana chapter of Sigma Xi. Because of the profound influence that this new doctrine has already had upon philosophic thought and the attention it has directed to the foundations of mathematical physics, it is important that the most careful scrutiny should be given to the postulates which underlie it and to the experimental evidence upon which it rests. Recently the work of Professor Dayton C. Miller has threatened the experimental foundations of the theory and a reasonable doubt as to its validity has been entertained by a group of scientific men.

In order to give an opportunity for the presentation of evidence on both sides of this important question the Indiana Chapter of Sigma Xi extended an invitation to two mathematicians, an astronomer, and a physicist to debate the question. The result is contained in the present volume.

The meetings were presided over by Professor William M. Tucker, president of the local chapter of Sigma Xi, and the introductory address was made by President William Lowe Bryan. On the second evening Professor John B. Dutcher of the Physics department projected interference fringes upon a screen in order to give those present some notion of the delicate and treacherous phenomena whose study has been fundamental in the erection of the new theory.

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INTRODUCTION

It has been said that men fall into three classes according to their underlying assumption as to the nature of reality. The first class, which includes most of mankind, assumes that reality is static; the second that nothing is static but all things in eternal flux; the third that throughout the eternal flux there is everywhere and always intelligible reason. The three classes of men take these three attitudes toward the systems of human knowledge: The first class holds that certain systems of knowledge are the truth and are permanently valid; the second that no knowledge is permanently valid and that the truth can never be known; the third that throughout the incessant change in every minor and major part of human knowledge, reason survives and becomes always more apparent and more dependable for the guidance of conduct. Those who have the first view are alarmed at every major change in the system of science. Those who have the second view regard such changes as cumulative justification for skepticism as to the possibility of any valid science whatever. Those who have the third view regard the entire history of human knowledge from its beginnings with primitive man to the present as best understood when we regard it as a progressive discovery of reality through forms of knowledge which are never final. From this third point of view no new theory, however revolutionary, is judged a priori to be impossible. It must have its opportunity to show, if it can, that it

accounts for all facts old and new better than the theories which it would replace. But the more revolutionary the new theory the more difficult its task.

The Indiana University gladly welcomes scholarly debate upon the facts and issues involved in the Theory of Relativity.

WILLIAM LOWE BRYAN

THE FOUNDATION PRINCIPLES OF RELATIVITY

The Opening Arguments of the Affirmative by Professor R. D. Carmichael.

Upon receiving the invitation to speak on this occasion I expressed an unwillingness to engage in debate on relativity in the spirit of seeking a victory over my opponents, but said that I would enjoy a debate in the spirit of a search for the truth. I added a statement of my assurance that the latter was intended, since such a chapter of Sigma Xi as I know that at Indiana to be would sponsor no debate except that which has the search for and exhibition of the truth as its guiding purpose. This occasion is one of great pleasure to me in that it allows me to renew my association with that chapter of Sigma Xi which did me the honor of electing me into this excellent society. I return to you with joy as to my Alma Mater in Sigma Xi just as I returned here last year with joy to my Alma Mater in Phi Beta Kappa to deliver the annual oration. This double memory of me by my friends in Indiana University, and these so closely connected invitations to appear before you in two so widely separated fields, are very gratifying to me; and I want here and now to express my appreciation of them.

On the matter of relativity I have definite convictions, but I hold them subject to revision in the presence of new discoveries or unexpected logical

difficulties in the theory itself. I held these convictions (or at least some of them) at a time when many people ridiculed the idea of relativity; and I delivered at Indiana University in 1912 (but not without trepidation) what appears to have been the first course of lectures on relativity given on the American continent, having been inspired to do this by the kindly encouragement of Professor Rothrock; and the notes of these lectures were published in a little book which is now in its second edition.

During the intervening years I have continued to believe in the theory and have witnessed with pleasure its growth and development. I have enjoyed seeing it gain adherents year by year so that now it no longer requires courage to uphold the theory. On the contrary it requires courage to oppose it. From time to time I have heard reports of the destruction of the theory and rumors of such reports. Formerly they caused me a certain flutter of excitement, but now they do so no longer. I have seen the theory of relativity gaining place in spite of all such reports and all rumors of such reports. Consequently I am not alarmed by the new and important experiments of D. C. Miller which have so renewed the hearts of the opponents of the theory; but I expect them, when the actual findings are determined with accuracy, to take their place in the theory of relativity or in a modified form of it.

The evidence now appears to me to be conclusive that the theory of relativity has come to stay, not without development and improvement to be sure, but without such change as will destroy its essential character. It may be included in a later and more comprehensive

theory in the same way as that in which it has included its predecessors, but thinkers will never return to the old way of thinking in vogue before the appearance of relativity.

If I am wrong in this conviction and confidence, I count myself fortunate now to be in a position to receive my due punishment for such error; for I believe with Socrates, as reported by Plato, that the due punishment of a man for error is to be set right by those who know. Therefore in undertaking to uphold my conviction and to transfer to you my confidence in the theory of relativity, I count myself doubly fortunate to meet two such speakers and thinkers as the local chapter of Sigma Xi has opposed to me in this friendly encounter—an encounter, I believe, whose spirit is that of search for the truth, unmarred by the desire for personal victory.

At the opening of this debate I am reminded of a happening at the time of the last preceding great advance in scientific thought, comparable to relativity both in importance and in the stir of public interest and curiosity which it excited. I refer to the famous Huxley-Wilberforce debate on Darwin's theory of evolution. In that great encounter the Bishop, primed with "facts" misunderstood, came forth

"To meet, for the first time in all his life,
Stark earnest thought, wrestling for truth alone,
As men on earth discerned it"

and seemed to many of his auditors to win clear victory; but according to the verdict of history, he suffered ignominious defeat. As for his opponents (I quote Alfred Noyes),

"They trusted in the truth. They could not see
Where it might lead them. Only at times they felt
As they deciphered the dark Book of Earth
That, following its majestic rhythm of law,
They followed the true path, the eternal way
Of that which reigned."

After the tumultuous applause which followed the Bishop's well rounded oration

"The lean tall figure of Huxley quietly arose.
He looked for a moment thoughtfully at the
crowd,
Saw rows of hostile faces; caught the grin
Of ignorant curiosity: here and there,
A hopeful gleam of friendship; and, far back,
The young, swift-footed, waiting for the fire
[Of truth to carry on the conquering Torch].
He fixed his eyes on these—then, in low tones,
Clear, cool, incisive, 'I have come here,' he said,
'In the cause of science only.'"

In this debate we are fortunate in the fact that both sides have come here in the cause of truth alone; and in the spirit actuated by such a cause we shall carry on our discussions. Though relativity is new the time has come for it to win; and I am here tonight to add a little bit of impulse to hasten the day of its final triumph.

But the problem of relativity is far too serious a matter to be settled by such a debate as this. A full analysis of the subject requires the technical machinery of a complicated and advanced mathematics; and this is clearly out of the question on the present occasion. We can not here settle the argument; we can only hope

to advance it in the minds of some of you.

No sort of mechanics can be developed without some kind of principle of relativity. There is a certain sort of relativity of space involved already in the old geometry of Euclid, as Birkhoff has so happily emphasized in his recent book on *"The Origin, Nature, and Influence of Relativity."* This is modified in the more restricted relativity involved in the Galileo-Newtonian mechanics; and the latter theory of relativity—without being called by this name—has flourished for several generations in the classical theoretical physics. A new and more comprehensive relativity was introduced by Einstein in his restricted theory as presented in 1905. The most significant extension of this was made by Einstein himself in his memoir of 1916; and this theory has been developed and extended and modified by others since then, notably by Weyl and Eddington and Whitehead.

It becomes, then, a question, not of having or not having a theory of relativity, but of what theory of relativity one shall hold. The name Theory of Relativity, by a sort of historical accident, has become attached to that sort which has been developed by Einstein and his followers. We may call it "the Relativity belonging to the Einstein tradition". In opposing this theory of relativity, our opponents, it is to be presumed, will tell us what theory they profess and will undertake to remove the difficulties which we may show it to possess.

For our part we shall support the relativity belonging to the Einstein tradition.

Such relativity will be modified and extended and

developed, but we will never go back to the older ways of thinking. What has been achieved is not perfect; it is not ultimate. There is nowhere a scientific theory which is perfect and ultimate. But the theory of relativity comes nearer to this ideal than any of its rivals. The cause of the older physics, in so far as it is opposed to relativity, appears to me to be already a lost cause, even though there are still those who are ready to support it. Its advocates are evidently alive though the cause itself seems to be lost. And a cause once lost nearly always remains a lost cause.

Before we proceed to an analysis of the basis of the general theory of relativity we must give attention to still a few other preliminary considerations.

It is necessary to draw a careful distinction between the laws and the principles of physical science. The two things are different though they have not always been sharply distinguished. It is very important to us now to draw the distinction; and it is convenient to use these two words to express the difference in thought.

By a law we shall mean a statement of phenomenal fact in terms involving numerical relations subject to experimental verification by measurement. By a principle we shall mean a statement of fact, relating to phenomena, in such a form as to require a transformation by the use of other facts before one can arrive at numerical relations subject to experimental verification by measurement.

With this use of terms we should speak, for instance, as is customarily done, of the Principle (rather than the Law) of the Conservation of Energy. But we shall speak of Newton's Law of Gravitation. The

former expresses a general principle which must be transformed by means of other facts before one can arrive at numerical relations subject to experimental confirmation by measurement; the latter states a phenomenal fact (in so far as it is true) in terms of a numerical relation subject to experimental confirmation by measurement. Following this terminology, we should speak of the Principle of Evolution and Mendel's Law of inheritance.

Both laws and principles have been of fundamental importance in the development of physical science. We can not dispense with either of them. But the principles of physical science are not subject to a direct proof or disproof. This is true of the Principle of the Conservation of Energy. There is no direct proof of it; and in the nature of things it is difficult to see how there could be. And yet it is of so fundamental a character that without it the structure of modern physical science would collapse. It may be modified; it may be combined with the Principle of the Conservation of Matter into a new form which embraces the two older principles. But we can not dispense with it without building up the whole of our science on some new basis not yet known to us. The value of the principle is in the guidance which it affords both to experiment and to a logical organization and coordination of physical science. Many of the results attained or explained by aid of it, in conjunction with other facts, are subject to experimental verification; but the principle itself is not subject to direct test. Its value and presumptive accuracy are determined by an analysis and examination of the results obtained by means of it.

No one disputes the value of what has been achieved by means of the principle of the conservation of energy; and therefore no one can properly object to a principle on account of the fact that it plays a role similar in the respects indicated to that of the principle of the conservation of energy.

Now one main part of the basis of the theory of relativity rests, as we shall see, in certain principles which underlie the development of the theory. When we come to them it will be well to remember the role of a principle as exhibited by the examples just given.

It is important to have clearly in mind the relation of relativity to the facts of physical phenomena before we proceed to the analysis which is to result in the principles of relativity.

There is no experimental fact, tested and corroborated, which is clearly known to be in contradiction with relativity. There are facts, of course, which have not been brought under its domain. This is fortunate, since a comprehensive synthesis might represent a dead end, leading to no further progress for a long time; but the quantum theory has appeared with a new set of facts partially outside the scope of the present relativity physics; and these new facts beckon us to further discoveries not yet made. There are facts, then, which have not been brought under the domain of relativity; there are some which have been erroneously thought to be in contradiction with it; and there are some about which we do not know what to say at present for lack of sufficient evidence or of a sufficient analysis. If the debaters here can present any facts which they think to be in contradiction with the theory

of relativity we will do one of four things, so far as time will permit; we will undertake to show that the charge of contradiction is not convincingly supported, or we will repel the charge with convincing evidence, or we will show that the facts alleged do not come within the domain of the present relativity physics, or we will acknowledge either the validity of the charge or of our inability to refute it. Unless some fact or facts at present unknown to us are given we will refute the charge of established contradiction. We admit the possible existence of conclusions about which we can not say with certainty whether they contradict or support the theory of relativity, because nobody knows with certainty. Obviously we can not marshal all facts and show their agreement with relativity; but we are prepared to examine all facts presented and to deal with them as we have already said.

We believe furthermore that no such comprehensive agreement with phenomena can be claimed for any rival theory.

In this connection it is important to remember that most observed phenomena are in agreement both with relativity and with the classical theory, the two doctrines giving rise to conclusions which are so nearly identical, so far as observational confirmation is concerned, that the numerical differences are within the limits of experimental error.

My colleague will tell you about the remarkable conquests of the theory of relativity in connection with the three so-called crucial experiments suggested by Einstein. I may anticipate his analysis to the extent of saying in a preliminary way that the theory has ex-

plained the long-standing anomaly in connection with the perihelion advance of Mercury, that it has predicted the bending of a light ray in the neighborhood of the sun and that this prediction has been verified, and that it has predicted the shifting of spectral lines in light coming from the sun or other large bodies and that this prediction has been verified by observation not only of light from the sun but also of that from the White Dwarf, the illustrious companion of Sirius. You see that the theory has been verified by crucial phenomena arising in the solar system and by phenomena from regions beyond the confines of the solar system.

Thus Einstein has given us signs in the heavens to corroborate his theory and mankind will never go back on signs in the heavens. A theory so supported by celestial witnesses is one which has come to stay.

In a letter to a London paper a few years ago Einstein said that if relativity should prevail then in Germany he would be a German scientist while in England he would be a German Jew, whereas if the theory should fail to be confirmed then in England he would be a German scientist while in Germany he would be a German Jew. If this relativistic proposition is true, then the Germans will call Einstein a German scientist while the English will call him a German Jew.

What is the origin, what is the nature, and what is the import of a system of thought which conquers on the earth and in the silent depths of distant space? To answer this question is our present task.

The position of a ship at sea may be defined by giving two numbers, its latitude and its longitude; it is a two-dimensional matter. To define the position of an

aeroplane at sea requires latitude and longitude and height above sea-level; it is a matter of three dimensions. In both of these cases we have spoken of positions merely. The primary things of physical science are not positions but events, things which happen. Now nothing ever happened in a portion of space without happening also in an interval of time. To locate an event we have to specify four numbers; it is a matter of four dimensions. In the usual language three of these are said to belong to space and one to belong to time. According to the theory of relativity the space and the time of an event are not two independent things. This is the primary innovation of Einstein. To assume that they are independent, as was universally done before the advent of the theory of relativity, is to introduce into our interpretation of phenomena an element of hypothesis which is not supplied by the facts. On this hypothesis we can build a mechanics which has a certain very close approximation to the facts as we know them. But if we want a thoroughly adequate account of phenomena we must proceed to more fundamental considerations and we must deny ourselves the apparent convenience of the hypothesis of a fundamental sepaiation of space and time.

It is desirable to dwell a little longer on the fact that the fundamental things in physical science are events. There is no such thing as an atom at an instant of time. It requires a certain interval of time for an atom to be an atom. A manifestation of activity is one of the things necessary to its existence as we conceive it, and activity can not be manifested at an instant; a certain

duration of time is necessary to the exhibition of its properties and hence to its existence as we know it. Moreover, a certain portion of space, and not a mere point, is necessary as the scene of its activities. It is in connection with these facts, more than any other, that the Einstein synthesis falls short of the ultimate. It uses a special model of interstellar space, empty except for point particles, and it conceives time as made up of instants. This is a conception of things which is not true to facts and it can hardly be supposed that any theory is ultimate which begins from a conception, or a model, of things not in entire accord with phenomena. There is then, apparently, something yet necessary to bring the Einstein synthesis to the highest conceivable perfection. Whitehead has made an important contribution in this direction, but there still remains much to be done. While the Einstein theory has moved in the right direction it has not yet reached the goal of the ultimate.

Let us linger a little longer over one element in the notion of an event in order to emphasize the fact that events are not matters in which space and time are separated. An event takes place where it occurs and when it occurs, and the where and the when are not separated in experience but are in the most intimate union and conjunction. It is only in thought that we have separated them. For a time this separation in thought was useful and convenient to us, but it has lately led us into difficulties. What more natural thing, then, could be done than to agree to dispense with a convention which has served its purpose and has finally become uncomfortable to us? In the theory of rela-

tivity we propose to do away with this convention and to allow space and time to be commingled in our thought as they always have been in our experience. Henceforth, in thought as well as in experience, space by itself and time by itself, as Minkowski has said, are to be mere shadows and only a union of the two shall be conceived as having real existence.

Let us enquire how this radical return of thought to the basis of experience has come about.

If a swimmer can go a certain distance d miles in still water and return in t seconds, his velocity being c miles per second, then in a stream flowing with a velocity of v miles per second he can swim directly across a distance d and return in st seconds where

$$s=1/\sqrt{1-v^2/c^2}\ ,$$

and he can swim a distance d upstream and back in s^2t seconds. These two times differ by a measurable amount. If the times were determined by experiment and the velocity of the swimmer in still water were known, one could compute the velocity of the stream.

The principle involved in this simple example underlies the experiment from a consideration of which the theory of relativity took its rise. If the earth is moving through the ether of space (supposed existent at the time the experiment was made) this fact should affect the phenomena of light and of electromagnetism. In particular, a light ray should make its journey across the ether stream to a mirror and back in less time than would be required if the same journey were made along the ether stream and back. But the early experiments of Michelson and Morley showed no such

difference in time. These experimenters failed to detect a motion through the ether. (On account of the recent work of D. C. Miller a further analysis must now be made of the Michelson and Morley experiment: this we shall give you tomorrow night.) Several other experiments were made in the attempt to detect motion through the hypothetical ether, and all of them showed a negative result. It was impossible to detect any effect whatever of the supposed ether upon the facts of experiment, though trials of various sorts were made. Even in the light of the recent experiments of D C. Miller, as we shall show more fully tomorrow night by an examination of that experiment and several others, the preponderating evidence is still in favor of the conclusion that motion through a hypothetical ether can not be detected by observation of phenomena on the moving system. There is too great a convergence of evidence from several sources for us seriously to question the conclusion on the basis of a single experiment the implications of which are not yet fully understood, even though that experiment is acknowledged to be one of fundamental importance.

Now no one has ever succeeded in assigning to this hypothetical ether a set of consistent properties which will bring the hypothesis of its existence into agreement with all the relevant facts. This does not mean that no one will ever do so; but it does justify us in formulating our laws and principles of nature in a form to be independent of the ether, if we are able to do so; and in the theory of relativity a reasonable success in this direction has been made. Let us then, for the present, formulate some of the conclusions of experimental

fact without employing any conception of the ether. We will do this in general terms for the sake of brevity. In the first analysis we shall suppose that the gravitational field is sufficiently small to be treated as negligible.

In order to be able to deal with such quantities as are involved in the measurement of motion, time, velocity, etc., or, indeed, in the quantitative analysis of any physical phenomena, it is necessary to have some system or systems of reference with respect to which measurements can be made. Let us consider any set of things consisting of objects and any kind of physical quantities whatever, as electric charges or magnets or light-sources or telescopes or other objects and instruments, each of which is at rest with respect to each of the others. Let us suppose that among these objects are clocks, to be used for measuring time, and rods or rules to be used for measuring lengths, and that time and length may be measured at any desired instant and any assigned place. Such a set of objects and quantities and instruments, including the equipment for measuring time and length, all being at rest relatively to each other, we shall call a system of reference. Such a system we shall denote variously by S, S', S_1, S_2, etc.

In order to formulate some of the principles we need also the conception of free space. Free space is a portion of space in which no gravitational or electromagnetic or other field is present. In practice we shall use for free space any portion of space in which such fields are so weak as to be negligible.

The Restricted Principle of Relativity may now be stated in the following form: *If S_1 and S_2 are two sys-*

tems of reference in free space having with respect to each other a uniform unaccelerated motion, then natural phenomena run their course with respect to S_2 in accordance with precisely the same general laws as with respect to S_1.

This principle says nothing about the suitability of any particular system of reference for the convenient expression of the laws of nature; but it does say that if either S_1 or S_2 is suitable the other is equally suitable, when the conditions named are satisfied.

In order to bring into convenient relations the measurements made on two systems of reference it is necessary to have some agreement concerning the correspondence of units. Accordingly, we shall make use of the following Principle of Correspondence of Units. The units of any two systems S_1 and S_2 are such that the same numerical result will be obtained on measuring with the units of S_1 a quantity L_1 and with the units S_2 a quantity L_2 when the relation of L_1 to S_1 is just the same as that of L_2 to S_2.

Let us suppose that the restricted principle of relativity is to be understood in a sense which implies this agreement concerning the correspondence of units. As so interpreted we believe that the restricted principle of relativity is in agreement with the facts of experiment and observation.

There are two characteristic postulates or laws of nature implied by the restricted principle of relativity. They may be stated as follows:

The unaccelerated motion of a system of reference S in free space can not be detected by observations made on S alone, the units of measurement being those

belonging to S.

The velocity of light in free space, when measured on an unaccelerated system of reference S by means of units belonging to S, is independent of the velocity of S and of the unaccelerated velocity of the light source.

There are three other postulates or laws which we now need, and these are common to the restricted theory of relativity and the Galileo-Newtonian mechanics. They may be stated in the following form:

If two systems of reference S_1 and S_2 move with unaccelerated relative velocity and if a body moves relatively to one of the systems in a straight line with unaccelerated velocity then it also moves in a straight line relatively to the other and with unaccelerated velocity.

If the velocity of a system of reference S_2 relative to a system of reference S_1 is measured by means of units belonging to S_1 and if the velocity of S_1 relative to S_2 is measured by means of units belonging to S_2 the two results will agree in numerical value.

If two systems of reference S_1 and S_2 move with unaccelerated relative velocity and if a line segment l is perpendicular to the line of motion of S_1 and S_2 and is fixed to one of these systems, then the length of l measured by means of the units belonging to S_1 will be the same as its length measured by means of the units belonging to S_2.

It should be observed that the last three postulates are merely explicit statements of principles which underlie the classical Galileo-Newtonian mechanics; they are common to that theory and the restricted theory of relativity. Since the latter may be derived in toto

by means of these postulates and the restricted principle of relativity, together with the characteristic laws implied by it, it follows that all adherents of the Galileo-Newtonian mechanics must find in the restricted principle of relativity alone the ground for their objections to the theory. We may therefore expect this principle to play an important role in our further discussions.

From these postulates one may readily derive the formulas for the celebrated Lorentz transformation of space and time coordinates. Let two systems of reference S and S' have the relative velocity v in the line l. Let systems of rectangular coordinates be attached to the systems of reference S and S' in such a way that the x-axis of each system is in the line l and that the two axes have the same positive direction; and let the y-axis and the z-axis of one system be parallel to the y-axis and the z-axis respectively of the other system and have their positive senses in the same directions. Let these two axes coincide at the time zero. Furthermore, for the sake of distinction, denote the space and time coordinates on S by x, y, z, t, and those on S' by x', y', z', t'. Let us suppose that S' moves with respect to S in the direction of increasing values of x in the system on S. Then it may be shown, on the basis of the named postulates, that the values of t', x', y', z' in terms of t, x, y, z are expressed by the formulas,

$$t' = \frac{1}{\sqrt{1-\beta^2}}\left(t - \frac{v}{c^2}x\right),$$

$$x' = \frac{1}{\sqrt{1-\beta^2}}(x - vt),$$

$$y' = y,$$
$$z' = z,$$

where $\beta = v/c$ and c is the velocity of light. These formulas define the Lorentz transformation.

It is important to remember that the Lorentz transformation already had a fundamental place in physical science before the advent of the theory of relativity, but it was not grounded in a general principle of fundamental importance as it is in relativity. It is the great glory of Einstein that he saw how to ground it in a general principle and later to proceed from it to his fundamental theory of gravitation.

It is not difficult to show that all the essential parts of the restricted theory of relativity are bound up in these equations and the interpretation of them which is implicit in the method by which they are derived. It is therefore important to our present purpose to put a part of their meaning into common every day language, such as may be understood by those who are repelled by the mathematical formulas.

The first truth that we shall associate with them is one which was discovered by Einstein: *There is no such thing as the absolute simultaneity of events happening at different places.*

It is important to get a clear grasp of the implications of this statement. What shall we mean by saying that two events which happen at different places are simultaneous? First of all let us notice that we have no direct sense of what such simultaneity should mean. Two experiences which I myself have may be called simultaneous if they are so interlocked that I can not separate them without mutilating them. But if two

things happen which are far removed from each other I do not have a direct perception of them in such a way as to perceive them as *simultaneous*. When should I consider such events to be simultaneous?

If you examine this question with a clear analysis you will see that you can not give any absolute answer. It is necessary to invent some technical means of defining such simultaneity. The definition will depend upon the system of reference from which measurements are being made; and it will be different for two observers upon systems which are not at rest relatively to each other. There is therefore a certain element of convention or agreement in every such definition. There is no such thing as absolute simultaneity of events which are separated in space; simultaneity is a relative matter.

It is, however, not an arbitrary matter. While it is not defined by any absolute means it is yet restricted within certain limits. Let us make clear the nature of this restriction. In this analysis we need to make use of the fact that the velocity of light is the greatest velocity which exists in the physical world. No object or disturbance has ever been known to move faster than light. There is an inherent impossibility in the well known limerick:

"There was a woman named Wright
Who moved about faster than light.
She went out one day
In a relative way
And returned the preceding night."

Now consider a particular event, as the running of this watch, for instance. Let us use the phrase, the

active past of this event, to denote those happenings in time which are close enough, relatively to their position in space, to have a possible chance of affecting this event. In the four-dimensional world of space and time this will be a cone stretching backward in time from the running watch which is at its vertex. Every happening in this cone—and no other—will be said to belong to the active past of this event afforded by the running watch. A happening five hundred years ago on a star a thousand light-years away is too recent to be in the active past of this present event here, since no influence from it has yet had time to reach this event. Moreover, nothing within the next thousand years can happen here so as to affect the star which is a thousand light-years away, since no influence arising here and now will reach it in less than a thousand years. Thus we are led also to the conception of the active future of this present event. This active future consists of all the happenings which are close enough in time, relatively to their position in space, to have a possible chance of being affected by this present event. This active future is a cone in the four-dimensional world of space and time which stretches forward in time from this present event which is at its vertex.

Thus the active past of this event is a four-dimensional cone stretching backward in space and time; while its active future is a similar cone stretching forward in space and time. Any part of the four-dimensional world which is outside of both of these cones is neither in the active past nor in the active future of this present event. All such parts of the four-dimensional world may be said to be contemporaneous

with this present event. Thus physical time has a sort of conical order, as Robb has called it, and not a linear order. It is due to this fact that simultaneity can not be an absolute matter while it is also not an arbitrary matter. By any proper definition of the simultaneity of two events, neither must be in the active past or in the active future of the other. Each must be in the region of contemporaneousness with the other. Within the limits thus set simultaneity may be defined in any convenient way. We can not now go into the technical means by which simultaneity may be conveniently defined on a particular system of reference, inasmuch as that is not necessary to the analysis of the principles of relativity as we are now developing them.

Let us point out some other consequences of the Lorentz transformation and hence of the restricted theory of relativity. To an observer A on one system the clocks on another system in relative motion with his own will appear to run more slowly than his own, while to an observer B on the second system the clocks of the first system will appear to run more slowly than his own. To each the unit of time of the other appears to be greater than his own. Again, to each of them it appears that the unit of length of the other, in their line of relative motion, is longer than his own. These differences are inherent in the nature of things and can not be effectively removed by any conventional agreement. Addition of velocities follows a new law. The velocity of light is a maximum velocity in nature. The mass of a body increases as its velocity is increased, so that there is a tendency to treat mass and energy as essentially interchangeable. But, above all, space and

time are entangled and commingled so as to be quite inseparable. Thus theory has kept together the space and the time which have always been commingled in our experience.

After the severe shaking up due to the restricted theory of relativity and the experiments out of which it grew, theoretical physics was ready to start over again and to make further progress with the problems of space and time and motion—the most important and the most fruitful problems with which physics has had to deal. The essential step of progress was made by Einstein with his general theory of relativity announced in his memoir of 1916.

Now if space and time are conjoined or entangled in experience so that we can no longer profitably separate them in thought, we are not justified in dealing with a space of three dimensions separated from the one time dimension, but we must deal at once with the one thing which we may call space-time—not space and time, not the addition of two things, but one thing, a thing for which we have no word, since it is a new conception. We call it space-time for lack of a better term.

This four-dimensional manifold of space-time is the fundamental starting point of the general theory of relativity. In physical science it is essential that we say both where and when a thing is or an event occurs—and these are not two things but one. They can be separated only by a convention that has an element of arbitrariness in it. It is due to the inadequacy of language that we have to speak as if we referred to parts conjoined. Having no words for the whole we have

to refer to the artificial parts which language names. But, nevertheless, let us hold clearly to the fact that to call for where and when is to call for one thing, namely, the space-time location of an event.

Keeping these considerations in mind let us lead up to and present the basic principles on which Einstein founded his general theory of relativity.

In the first place we must keep clearly in mind a fact which has sometimes been lost from view. The restricted theory of relativity was not discarded in formulating the general theory; on the contrary, the former was wrought intimately into the structure of the latter. In the process it became evident that the restricted theory was subject to some limitations not at first fully realized—limitations as to the circumstances of its validity. But with these limitations, which we have wrought into the foregoing formulation, this theory has been incorporated into the general theory. This has been done in two definite and specific ways, as we shall now make clear.

In the general theory it is still maintained that the restricted principle of relativity shall hold, subject to the stated condition that the phenomena involved occur in free space. This affords a sort of limiting condition by means of which certain properties of the gravitational potential may be established. There is no condition in nature in which this principle can be applied with strictness just as there is no condition when undisturbed motion in a straight line can be realized in the Newtonian mechanics. But it is an ideal condition which reflects itself in limitations on the form of the gravitational potential; in this way it comes to be sub-

ject to indirect experimental test. The maintenance of the restricted principle of relativity in free space serves to afford limiting conditions or boundary conditions at infinity, so to speak; and these are essential to the development of the general theory.

In connection with Newton's law of gravitation you have all heard the story of the falling apple. Since Einstein has given us a law of gravitation to replace that of Newton it is fitting that a like story of a falling object should be associated with him. I do not vouch for its historical accuracy, but it affords a convenient means of introducing an important principle.

The story is told that Einstein was watching a laborer on a high scaffold engaged with others in the construction of a building and that he saw the laborer lose his balance and fall to the ground. Fortunately the laborer was not seriously hurt. On seeing this, so the story goes, Einstein ran up to the laborer in great excitement, and the following colloquy took place:

"My dear sir, did you feel anything pulling on you as you came down?"

"What?"

"Did you feel anything pulling on you as you came down?"

"No, I just fell."

The laborer could not see that he needed to have anything pull on him to make him come down. He just fell.

Let us idealize this story into a sort of mental experiment. Let us suppose that an observer is inclosed in a sealed laboratory so that he can observe nothing except what is taking place in his laboratory. Suppose

that the laboratory is unsupported by other bodies and that it is falling freely in space without rotation. If in such a laboratory an object is placed at a given point in the open air it will remain fixed there. If it is given a motion in any direction whatever relative to the walls of the laboratory it will continue in motion in a straight line relative to the walls of the laboratory until it is impeded by some resisting force. An observer in such a laboratory would find himself, to all intents and purposes, in a state of freedom from any gravitational field whatever. Weight has disappeared. If one leaps upward with ever so little force he will go to the top of the laboratory. If he takes his place in the middle, not touching either top or bottom or walls, he will remain stationary there. The gravitational field is non-existent for him. The relativity of the situation is incomplete, however, as would be shown by the behavior of a magnetic needle.

Now what does this absence of a gravitational field signify? Within this laboratory phenomena (events) run their course independently of gravitation, provided that they are considered only in their relation to the laboratory itself and to one another in the laboratory.

But now suppose that the laboratory is falling toward the earth and is being observed from a station on the earth. It is found that it is falling with a constantly increasing velocity; that is, it is subject to an acceleration—just the acceleration which is due to the gravitational field through which the laboratory is moving. It is this acceleration which has balanced, or dispensed with, the gravitational field. We may say that, so far as the laboratory is concerned, the acceleration

field is equivalent to the gravitational field and is oppositely directed so that the two fields balance each other.

Now suppose that some upward pull decreases the acceleration of the laboratory relative to the earth without overcoming it entirely. A part of the gravitational field will still be overcome, but another part will remain and manifest itself as a reduced gravitational field in the laboratory.

Let us now reverse the pull on the laboratory and bring it down with a greater acceleration than that due to the gravitational field of force. What will then happen to the objects within the laboratory? They will all *fall* to the top of the laboratory and will remain stationary there; and it will require force to *lift* them from the top just as it ordinarily requires force to lift objects from the bottom of our laboratories stationed on the earth. This means that the gravitational force is not only balanced out in the laboratory but that it is actually reversed in direction. We have introduced an acceleration field which is too strong for the gravitational field and has effectively reversed it in direction so that we have a gravitational field upward instead of downward.

What I want you to see from this is the following: By the introduction of an appropriate acceleration we can modify or annihilate or even reverse the gravitational field of force in the moving laboratory. By an appropriate pull of the laboratory to one side we could also produce a sidewise gravitational field.

Now if an acceleration field can so modify locally a gravitational field and even reverse it, there must be

some sort of fundamental equivalence between the two. This general conclusion may be formulated more precisly as one of the important foundation principles of the general theory of relativity. It means that we should choose as our fundamental four-dimensional geometry one in which we should no longer find it necessary to postulate forces to account for motions in a given sufficiently small portion of space.

We shall attempt a precise formulation of this Principle of Equivalence in the following words:

For a sufficiently small region of the four-dimensional world of space-time, that is, a region so small that the variation of gravitation in it in both time and space is negligible, there exists a coordinate system, or system of reference, with respect to which gravitation has no appreciable influence either upon the motion of mass particles or upon any other physical phenomena whatever.

As a commentary we may add the remark that if there is no electro-magnetic or other field present it is to be understood that the restricted theory of relativity is valid in this small portion of space-time, since it is then effectively a small portion of free space. This is the assumption made by Einstein and it is abundantly justified by the fact that the restricted theory is in such close agreement with so many phenomena of observation and experiment. It is not a speculative hypothesis but one that seems to be demanded by the facts of nature.

Thus we see that there are two ways in which the restricted theory of relativity is incorporated intimately into the general theory. To put it roughly, they are

the following: In the absence of a gravitational field and of electromagnetic or other disturbance, the restricted theory of relativity is to hold; in sufficiently small portions of space-time it is valid within the range of a vanishing difference due to macrocosmic phenomena.

There is still one other general principle upon which Einsetein has insisted, namely, the so-called Principle of Covariance. The following considerations will enable us to arrive at its meaning.

When a mathematician or a theoretical physicist wishes to speak in detail about physical phenomena, and especially the phenomena of motion, he introduces a system of coordinates x, y, z, t by means of which to define the positions of particles at the various instants of time. Now there are no such coordinates in nature. No one ever saw these quantities x, y, z, t either stationary or moving around among phenomena. They have been inserted by the thinker into the picture from which they are absent in nature. There is no objection to having this done, since it serves a great purpose of convenience. But proper allowance must be made for the fact that these coordinates x, y, z, t have been inserted into phenomena in which they have no place as a fact of the actual occurrences. They serve a useful purpose as a scaffolding to help sustain the thought during the process of investigation and discovery. But in the ultimate picture to be retained by science they can have no place since they are absent from nature. When the structure of science is completed this scaffolding should be torn away. It should not remain as a part of the ultimate explanation of

phenomena. These coordinates, having been introduced by thought as a matter of convenience, must be taken out of the picture formed by thought before that picture can be considered complete.

In more precise, but still non-technical language: The laws of nature should be so expressed in terms of the coordinates employed as to be essentially independent of the coordinates chosen so that if we used some other system of coordinates these laws should have in them the same expression as in those actually employed

The extreme naturalness of this requirement must be apparent to everyone, since elements not involved in phenomena should not form an essential part of the explanation of them. It is so simple in its general formulation that we may dispense with an exact mathematical statement.

We have now before us the three fundamental requirements of the general theory of relativity so far as gravitational fields are concerned. We shall not undertake to go into the extensions which have been proposed for dealing with electromagnetic phenomena, even though the latter are important, for all the essential questions concerning the validity of the relativistic point of view are, I believe, fully apparent in the theory of gravitation. By confining attention to this we will center our thought and make more effective progress toward understanding the theory.

Whether the laws of nature, as manifested in the results of experiment and observation, can be subject to these three fundamental requirements is the prime question to be answered in the general theory of rela-

tivity as it stands today. It is a question which can not be answered apart from experiment itself. To settle it requires much careful consideration. And the answer, as given up to the present, is an incomplete one, as is evidenced by the fact that people are interested in such a debate as this one. But, so far as present knowledge goes, it appears to me, as to many others, that the answer must be affirmative. My colleague will show you tomorrow night in how far the question has been actually answered in the affirmative by observation and experiment.

For my own part I must now say still a little more about the general principles underlying the theory, especially since the application of one of them has sometimes been misunderstood in such a way as to lead to a wrong conclusion.

According to the principle of equivalence it is possible so to choose the system of reference, in a limited portion of space-time, that the restricted theory of relativity will be valid except for inappreciable deviations from it. Now any other system of reference can be obtained from such a one by a transformation of coordinates. In such a transformation the space-time separation of two near events must be unchanged, for it is a quantity which is entirely independent of the system of coordinates. Let us denote this space-time separation of two near events by ds. Then in the restricted theory of relativity we have

$$ds^2=dx^2+dy^2+dz^2-c^2\,dt^2$$

where c is the speed of light, provided that we employ units which are both customary and convenient—a relation for which there is much experimental confirma-

tion. Now if we make a general transformation to new coordinates x_1, x_2, x_3, x_4, the foregoing equation takes the form

$$ds^2 = \sum_{ij=1}^{4} g_{ij}\, dx_i\, dx_j, \qquad g_{ij} = g_{ji},$$

where the g_{ij} are functions of x_1, x_2, x_3, x_4. Moreover, it is only an element ds of this form which may be changed, by transformation of coordinates, to that of the restricted theory of relativity. Hence the taking of a quadratic differential form for ds^2 has nothing arbitrary in it, but is required by the fact that the restricted theory holds in an infinitesimal region of space-time. This removes at a stroke some of the main objections which have been raised to taking a quadratic differential form as the defining form for ds^2. It is the only form which makes possible the maintenance of the principle of equivalence in the light of the fact that the restricted theory of relativity affords a first approximation to fact in a small portion of space-time even if there is a gravitational field.

Granting these three foundational principles of the general theory and starting from the deep-lying mathematical fact just given, one may build up gradually and step by step the details of the general theory of relativity. Unfortunately this can not be done (at present at least) without the machinery of a technical and advanced mathematics. From the mathematical point of view the first thing to be done is to determine what mathematical relations, involving the previously named coefficients g_{ij}, exist in such form as to satisfy the demand of the principle of covariance. This part

of the work is strictly theoretical, having no further relations with phenomena except those which have already been wrought into the expression for ds^2. It turns out that there are not many of these mathematical expressions having a relatively simple form. Consequently all of those of the simpler forms can be determined.

The question to be considered next is that of their relation to phenomena. There is no assurance beforehand that every one of them will correspond to events in the physical world; nor is there any *a priori* means for deciding which will belong to a given range of phenomena. That is a matter to be tested by observation and experiment. Now it turns out that one of the simpler ones is in close, but not exact, agreement with the Newtonian law of gravitation Since the latter is known to afford a close approximation to facts of observation, the covariant equation which corresponds to it is used to define the relativistic law of gravitation. It is that law which has brought the chief renown and glory to Einstein, since it has conquered in the realm of phenomena from the solar system and from regions lying beyond the confines of the solar system. In what way it has conquered my colleague will make known to you tomorrow night.

Let us now review briefly the general principles which underlie the theory of relativity in order that we may have a clear conception of their inherent simplicity. In so far as the theory differs from the classical mechanics these principles are four in number. The first is the so-called restricted principle of relativity. It asserts merely that the phenomena of nature run

their course according to precisely the same laws on any two systems in uniform relative motion in free space provided that either of them affords a suitable system for the convenient expression of the laws of nature. The second principle requires that in the theory of a gravitational field the first principle shall hold as a sort of limiting condition or as a sort of boundary condition at infinity. The third principle requires that the first shall hold with an indefinitely close approximation in an infinitesimal portion of space-time. And, finally, the fourth demands that the laws of nature shall be expressed in a form which is independent of the particular reference system used, this demand arising from the fact that there are no coordinates in nature so that the coordinates should virtually disappear from the laws of nature when expressed in their ultimate form.

One could hardly ask for a simpler basis than this for the deepest foundations of fundamental scientific theory. No other comprehensive theory in science yet proposed can vie with this in the simplicity and elegance of the fundamental basis from which it starts. In the neighborhood of a particular event in space-time, experiments may be carried out freely on any small moving body, and local distances, time intervals, pressures, densities, velocities, etc., may be treated with security by the usual methods, applied as if the moving body were at rest. The main elements in such phenomena consist of a microcosmic part—the part belonging to the local space-time—and there is only a slight macrocosmic deviation due to the presence of matter and the consequent curvature in the four-dimen-

sional space-time continuum. Gravitational phenomena appear as the manifestation of this curvature.

A complicated mathematical machinery, as we have said, is necessary in working out the details of the theory, but the basis of the analysis reaches the acme of simplicity. Simplicity in basis and complication in details is frequent in physical science. This is well illustrated even in so elementary a case as the classical theory of the tuning-fork. The general behavior of the tuning-fork can be theoretically explained only by elaborate considerations, no general formula has been found by means of which its fundamental note can be specified in advance. To deal directly with the atoms and electric charges of which it consists is quite impossible, and all we can hope to do in this direction is to obtain general average effects. The detailed theory would be enormously complicated; the reality itself is beyond the power of our minds to conceive adequately. It is an illustration of the fact that there is a great complication of detail in nature . "Simplicity and unity in the fundamental processes," as Birkhoff has said, "and yet an infinite complexity in their combinations seem more and more to be clearly manifested in nature."

Now you have before you the fundamental basis of the general theory of relativity, exclusive of its extension to electromagnetic phenomena, and an indication of the nature of its detailed development. Further into its foundations and into the problem of rearing the superstructure we can not go in the space of this lecture. How shall the theory be tested as to its adequacy? As in the case of any other theory which is ac-

ceptable it must meet three general demands of the human spirit, as follows: It must be in suitable agreement with the facts of nature; it must have those esthetic qualities which render it pleasing to the human spirit; and it must furnish what is to us the most agreeable theory from the point of view of convenience. A few words must now be said about these demands.

I have already spoken briefly about the agreement of the theory with the facts of nature. Tomorrow night the speakers will analyze this question in detail.

Whether the general basis of the theory is pleasing to the human spirit depends for the present upon the particular human spirit which is assessing it; and this will probably continue to be true for a generation or longer. But the whole basis of the theory is so beautiful and inspiring in its simplicity and elegance and is in such remarkable accord with the facts to which it is applicable that it appears to be inevitable that it shall come into general acceptance and that a future generation will understand only with difficulty how the people of our own day often found it so perplexing. When it was first learned that the earth is a sphere floating in space the statement of this fact seemed to many people to be quite absurd and out of agreement with phenomena. We ourselves are today so familiar with this conclusion that it is only with difficulty that we can understand how the men of a former time were nonplused by it. I confidently anticipate that the men of a future generation will look back to our own with the same feeling of wonder that we found it so difficult to adjust ourselves to the point of view of the theory

of relativity. When that day comes this theory will be quite satisfactory to the general human spirit.

How does the theory meet the demand for a convenient explanation of phenomena? No claim can be made for it that it is a unique explanation. In fact, as Poincaré has so cogently shown, if there is one explanation of a given body of natural phenomena then there is an infinitude of such explanations. Hence there is no question concerning uniqueness; it is already known that explanations are either non-existent or are infinite in number. It becomes then a question as to whether the theory of relativity affords the most convenient account of the phenomena subject to its jurisdiction; and this question, I believe, is to be answered in the affirmative.

If some of you are not comfortable in the presence of an insistence upon convenience as one of the qualities which a theory should possess, let me remind you that there is good authority for it in the writings of such an illustrious scientist as Copernicus, who says:

"Attacking a problem obviously difficult and almost inexplicable, at length I hit upon a solution whereby this could be reached by fewer and much more convenient constructions than had been handed down of old, if certain assumptions, which are called axioms, be granted me."

Now in the theory of relativity we grant ourselves certain principles (corresponding to the axioms mentioned by Copernicus) and by means of these we obtain a more convenient account of phenomena than any others which have been achieved without the use of these principles. And we are insisting upon the con-

venience of this procedure as being fundamental just as Copernicus formerly insisted upon the greater convenience of his now immortal system than that of any earlier theory. A chief element of this convenience consists in the fact that we do not have to employ *ad hoc* hypotheses to carry through our analysis, once we set out from the general basis of the theory of relativity.

Here we rest our argument for the present. It has consisted mainly in a development of the principles of relativity in a way to make their extreme naturalness and elegance apparent. The detailed analysis of the experimental evidence we have left to our colleague. Only incidentally have we shown the difficulties inherent in other theories; later we shall examine whatever alternative principles our opponents may offer. We shall hope to convict them of a misunderstanding of the true nature of the theory which we are upholding, if they should undertake merely to destroy our argument, on the ground that it is well to kill a rattlesnake lurking in a human path even though nothing else is put in its place. In any event, we shall return to the discussion tomorrow night in the spirit of a genuine search for right conclusions, convinced that to cover up the truth through fear or prejudice or the love of victory can never be the wisest way.

THE POSTULATES OF NORMAL INTUITION

The First Speech of the Negative by Professor W. D. MacMillan

The object of science is to coordinate and to interpret our experiences with nature, and to suggest the directions in which new experiences may be anticipated. This statement of aim implies a conscious mind which is to be satisfied and the existence of something external to it with which it has relations. We call this external something Nature, or Reality, or the Physical World, according to the mood we are in, but, whatever it is, it exists apart from and independent of the conscious mind which perceives it. I take it that as members of Sigma Xi we are all in agreement about this although there are and there have been and doubtless there will continue to be, men who assert that the conscious mind alone exists and that it is aware of nothing but its own activities. It is all a dream with nothing substantial, nothing real, back of it.

It will be perceived that I am making here my first assumption, namely that there exists an external reality which we call the physical world. If you do not choose to grant this assumption you and I are in disagreement from the start in the interpretation of our mental activities, and there is no hope that we shall arrive at a common conclusion. Neither of us can say that the other is wrong, for we have no common ground that will serve as the base of proof. We have

different points of view and that is the end of the matter. It is idle for you to assert that you are right and that I am wrong, and it is equally idle for me to make such an assertion. I will grant that to do so would be very human, and I think that you will grant that it would be very childish. That procedure leads only to quarrels and bitterness of spirit and is altogether undesirable. We shall let it go and try to find some other topic of conversation about which at least we can start together.

The history of human relations is a long story of quarrels and disagreements. In intellectual matters, however, the incentive for quarreling is not great. It does not go much deeper than the emotions of pique and vanity, and these emotions do not make a strong appeal to any one in his hours of reflection and meditation. We are interested in living together in peace and in profiting each by the experience of the other; and so when disagreement arises, if we are wise, we shall not pursue a quarrel, but we shall try to find the ground which we have in common; then patiently search for the point at which divergence sets in and let the conversation center calmly about this point. When this is done it is found that there are a large number of propositions so elemental in character that we can not get behind them, or offer any proof for the assumptions which we make with respect to them. It is extremely important, therefore, that we recognize the existence and nature of these fundamental assumptions, for they are, indeed, the foundation stones of our intellectual structures. They are so important that they have received a name. They are called *postulates,* and the

particular collection of assumptions which any one makes is called his *system of postulates.*

Let me give another example of a postulate, one that is familiar to every one, though, perhaps, not by that name. We recognize that most, if not all, physical things have a beginning in time, and an end also. The question arises—does the physical universe as a whole have a beginning? or, in common language, was it created? Many people make the postulate that it was. Scientists usually make the postulate that the physical universe had no beginning and therefore that it has always existed. As evidence on the matter is out of the question, one is free to choose either postulate and he is perfectly safe in his choice from the assaults of either evidence or logic. Scientists do not make the postulate that the physical universe was created for the simple reason that, for their purposes, such a postulate is utterly barren. If one wishes to assert that the physical universe was created this morning at 8 o'clock Central Standard Time, no one can successfully dispute him. If you say that you remember what happened yesterday, or last week, or last year, the answer is that your memories were created with you. If you say that the erosion of the continents and the fossils in the rocks indicate the lapse of many ages, you are confronted with the reply that the earth was created that way, and you are helpless. Of course, if one wishes to have his postulate say that creation occurred six thousand years ago or six million years ago, or a billion times six million years ago, he is perfectly free to do so. You may wonder why, with unlimited freedom, he should choose any particular time;

but whatever date he does choose you can not say that he is wrong. It is easy to see, therefore, why scientists in general do not make such a postulate. It does not help them in the explanation of anything. For their purposes it is barren and sterile and therefore useless.

It will be helpful, I think, to dwell a little longer upon the postulates that are commonly made with respect to this external reality which we sometimes call Nature, sometimes the Physical Universe, sometimes, perhaps, other names. It will be observed that I say they are commonly made. I do not say that they have been agreed upon, for such is certainly not the case. Intellectual men are very little disposed to agree about anything where disagreement is possible, and the domain of the postulates is precisely that domain in which they are perfectly free. I shall state these postulates as though they were facts, but any one who is so disposed may assert exactly the opposite without starting a quarrel.

The physical universe is continuous in time. This postulate asserts that the universe had no beginning and will have no end. It is at this point that we part company with many of the theologians.

The physical universe is not bounded in space. To say that it has no boundaries is equivalent to saying that it is infinite in extent.

There exist physical units, which for finite intervals of time preserve their identities and exhibit characteristic properties. Examples of these units are electrons, atoms, molecules, crystals, cells, stars, galaxies.

The sequence of physical units is infinite both ways. That is to say, *there is no largest physical unit and*

there is no smallest one.

The phenomena of nature occur always in such a way that certain relations remain invariant. This is merely a technical way of saying that processes of nature are orderly and that, therefore, science is possible. Any one who assents to this postulate, and sticks to it, is essentially a scientist. Any one who asserts the contrary, whatever else he may be, is not a scientist.

The energy within a region of space does not increase or decrease unless there is a corresponding decrease or increase in some other region of space. This is the doctrine of the conservation of energy and commands almost universal assent.

The universe does not change always in any one direction. That is, the universe does not flow like a stream from one unknown region into another. It is more like the ocean which, while never twice alike, is yet always the same.

I will mention only two more postulates, although many more could be set down.

The geometry of the physical universe is Euclidean.

The time of the physical universe is Newtonian.

This is the fork in the road where the modern school of relativity branches off. We must stop, therefore, and see what these postulates mean.

We must distinguish between the geometry of intuition and a mathematical geometry, or the space of intuition and a mathematical space. The space of intuition is the normal three-dimensional space in terms of which we are all accustomed to think. The geometry which has been built up from our intuitions is the geometry of Euclid, the geometry that is taught in

all of our schools. After having learned through our intuitions how to build up such a mathematical system, it is possible to vary the postulates on which the system is founded and to build up abstract geometries by means of pure logic. Such geometries are called non-Euclidean, and the corresponding spaces are called non-Euclidian spaces. They do not agree with the space of intuition, and the theorems with respect to them are the conclusions of a cold visionless logic. It is perhaps a misnomer to call them geometries at all, but whatever name is applied to these mathematical systems, our common Euclid belongs in the class.

According to the great geometer Riemann, there are infinitely many of these geometries. It all depends upon how the length of a curve is defined. Let us have a simple illustration. Suppose we had a metal plane, say of copper, which was indefinitely great in extent. Suppose further, that this plane was hotter in some spots than in others, and that our measurements on this plane were made with a thin steel ruler. The temperature of the ruler would vary as it was moved about on the plane, and its length also would vary with the temperature. The length of the ruler would depend upon where it was. It is needless to say that under such circumstances the familiar proposition of Euclid that the sum of the squares on the two sides of a right triangle is equal to the square on the hypothenuse would not be verified and the ratio of the circumference of a circle to its diameter would not be the well-known number π. It would not even be constant as measured by the steel ruler. Its value would depend upon where the center of the circle was and how large the diameter

was.

This is all simple and intelligible enough. But a mathematician will say, "Give me the coefficient of expansion of your ruler and the distribution of temperature over the plane and I will devise for you a geometry that will fit that plane. It will be necessary no longer for you to speak or think of variations in temperature. A special non-Euclidean geomerty is what you want." This is true enough and such a geometry might be helpful, but you and I who are accustomed to dwell in a physical world will prefer to think of the geometry of that plane as Euclidean and to ascribe the failure of our measurements to verify the theorems of Euclid to physical causes rather than to think in terms of a non-Euclidean geometry with which we can compute, but for which we have no intuitions. Doubtless the reason for this is that of all these infinitely many geometries the Euclidean is the simplest. The experience of the race has shown that we can always think in terms of it and charge the failures of our measurements to physical causes. It is not because the Euclidean geometry is truer than the non-Euclidean; it is not because the Eculidean geometry is intrinsically bound up with the physical universe; it is because it is simpler for us to impose the Euclidean geometry upon it and to think in terms of Euclid and of physical causes than to think in terms of an infinite variety of special geometries. This has been true throughout the long history of our race, and it is for this reason that our intuitions are Euclidean.

Let me take another example, this time from astronomy. In Euclid's geometry it is possible to draw

only one line through a given point parallel to a given line. In Lobachevski's geometry it is possible to draw infinitely many, and in Riemann's geometry it is impossible to draw any at all. In Lobachevski's geometry the parallax of every star, however distant, is positive and greater than a certain small number. In Euclid's geometry they are positive, but have the limit zero as the distance increases. In Riemann's geometry they are all negative. Let us appeal now to experiment. Let us measure the parallaxes of the stars and then decide. The experiment is very difficult and we are just able to make the measurements. The answer is not decisive Some parallaxes, as measured, are negative, but we ascribe these results to errors of observation. As for the others, the greatest is 3/4″, while the others seem to have zero as a limit, but the errors of observation are relatively great and we can not be sure. But even if they had all turned out negative we should not have adopted Riemann's geometry. We should simply have concluded that light, for some reason or other, did not travel in a straight line. There would have been a choice, and, as has always been the case, the trouble would have been thrown, not upon geometry, but upon physics.

Speaking upon this subject some twenty five years ago the great French mathematician, geometer, and physicist, Henri Poincaré, said: "Can we maintain that certain phenomena which are possible in Euclidian space would be impossible in non-Euclidian space, so that experiment in establishing these phenomena would directly contradict the non-Euclidian hypothesis? I think that such a question can not seriously be asked.

To me it is exactly equivalent to the following, the absurdity of which is obvious:—There are lengths which can be expressed in meters and centimeters, but which can not be measured in feet and inches."

Finally, in order to bring the matter within the range of the average man's comprehension, it was shown that a dictionary could be constructed by means of which the theorems in the geometry of Lobachevski and Riemann could be translated into the theorems of the ordinary geometry of Euclid, and vice versa. The mystery of these non-Euclidian geometries is now clear. They are merely different languages. Whatever can be said in Russian can also be said in English. We who have been raised to speak the English tongue are not going to trouble ourselves about speaking Russian just because we have recently discovered that a Russian language exists. We shall be quite content to believe that whatever we may have to say can be said in our own language.

I have dwelt somewhat at length upon the non-Euclidian geometries because their discovery about a hundred years ago by Lobachevski, a Russian, and by Bolyai, a Hungarian, created great excitement among the mathematicians of that time, and the question at once arose: which of these geometries is the true geometry? But after a hundred years of meditation upon the subject the excitement has largely died out, and from a practical point of view the matter has been summed up by Poincaré in the statement: "Euclidian geometry, therefore, has nothing to fear from fresh experiments."

In our own times a new excitement has arisen

among the mathematicians. Einstein has discovered a non-Newtonian mechanics, and immediately the fight is on: "Which is the true mechanics?" The mechanics of Newton, like the geometry of Euclid, was based upon our normal intuitions and it is, therefore, intelligible in the normal sense of the word, just as Euclid is intelligible. The geometry of Euclid is the foundation upon which the mechanics of Newton is reared. If to the subject of geometry are added the concepts of time, mass, and force and new postulates are added to state how these new concepts are to be measured, the new intellectual structure which arises is the subject of mechanics. These new concepts of time and force can not be defined, but they can be measured. Newton stated postulates by which this can be done, and these postulates are familiar under the name—Newton's Laws of Motion. Not only did Newton lay down these new postulates, but he developed the mathematical machinery that is necessary for tracing out the consequences of these new ideas. In the two hundred and fifty years that have elapsed since his work was first published, the subject of mechanics has been enormously developed upon the basis which he laid down. It has been the guide to all of our engineers in the marvelous achievements of modern times. It has furnished the ground work for all of our interpretations in the domain of physics, and, combined with Newton's own law of gravitation, it has explained the motions of the members of our solar system with such exactness that the subject of Celestial Mechanics seems almost to have attained that goal which is one of the aims of every science, namely,

complete and accurate prediction.

Newton conceived of time just as do all the rest of us. He thought of time as flowing onward, continuously and uniformly, alike for all; and therefore "Newtonian time" is sometimes called "public time". Whether a person be busy or idle, active or passive, awake or asleep, in Indiana or on the planet Mars, time flows on unceasingly and the same instant of time arrives everywhere simultaneously, irrespective of local physical conditions. It can be measured in different units such as days or years, just as distance can be measured in yards or miles. The particular unit employed is not material, but the time itself is the same everywhere.

At the very time when Galileo and Newton were laying the foundation of mechanics, studies were in progress as to the nature of light, and the great discovery was made in 1676 by the Danish astronomer Roemer that light does not travel instantaneously from one point to another, but that it travels at a certain speed which, while very great—186,000 miles per second—is not infinite. Even in Newton's day there were two theories as to the nature of light. The Dutch physicist Huyghens regarded light as a wave of some kind, while Newton regarded a beam of light as a stream of very small corpuscles which were emitted by a luminous body. The masterly exposition of the corpuscular theory by Newton and the great authority of his name maintained that theory in a dominant position until the beginning of the 19th century when the work of Young in England and Fresnel in France completely displaced it and gave to the undulatory

theory a dominance which it has held to the present time. According to this theory all space is filled with an ether which has the properties of an elastic solid, and light consists of transverse vibrations, like the waves on a stretched string, in this medium. Notwithstanding the properties assigned to the ether, large solid bodies, like the earth, move through it without disturbing it in any way.

Another field in the domain of physics came into existence early in the 19th century with the study of the phenomena of electricity and magnetism. The master investigator in this field was Michael Faraday. The ideas of Faraday were developed and put into mathematical form by Clerk Maxwell something more than sixty years ago. Maxwell showed that things happen just as though there existed at every point in the neighborhood of an electrical charge two forces, an electrical force and a magnetic force, just as the law of gravitation states that at every point in the neighborhood of every particle of matter there exists a force which we call gravitation. It was found further that the ratio between the electrostatic unit and the electromagnetic unit was, within the limits of experimental error, the velocity of light in the ether. This led Maxwell to perceive that an electromagnetic disturbance would be propagated in free space with the velocity of light, and to conclude that light was merely an electromagnetic disturbance. Thus the theory of optics and the theory of electricity which had not been previously suspected of having any relation to each other, were joined together in a more comprehensive theory—the theory of electro-magnetism.

The success achieved by this theory in accounting for all the known phenomena in its domain has been very great. It seemed about to rival in its perfection the attainments in the domain of Celestial Mechanics until Michelson performed, in 1887, what he himself has called his "unfortunate experiment". Just as the science of Celestial Mechanics rests upon a set of equations which result from the laws of motion and the law of gravitation, so the electro-magnetic theory rests upon a set of equations given by Maxwell, who regarded the electromagnetic disturbances as being propagated in an all pervading ether. The two sets of equations, dealing as they do with two quite different classes of phenomena, are naturally not at all alike. But there is one difference between them which has a philosophical significance. There is no suggestion that gravitation is propagated at all; or if one wishes to think of propagation, its speed is infinite; and the law of gravitation does not mention propagation. As a consequence of this the equations of Celestial Mechanics, which describe the motions of the planets of our solar system relative to the sun, remain unchanged whether the solar system is regarded as being at rest relative to the general system of stars or whether it is regarded as being in uniform motion along a straight line with any speed whetever. The equations of motion being just the same for the two cases there is no phenomenon in the system which would distinguish one case from the other. This is the old-fashioned, Newtonian relativity, which is quite agreeable to the philosophical instincts of most people. A point of absolute geometric space has no meaning.

It is different, however, with the equations of electro-magnetism. These were based upon the concept of an ether which fills all space and which has many of the properties of an elastic solid. A point which is fixed relative to the ether can be regarded as fixed relative to absolute geometric space, since the ether is not regarded as moving relative to absolute space. The velocity of propagation of the electro-magnetic waves, including light, being constant relative to the ether, can not be constant relative to bodies like the earth which do not have uniform straight line motion relative to the ether. Relative to such moving bodies the electro-magnetic equations are not the same as they are at rest relative to the ether. Since the equations are different one would expect the phenomena to depend upon absolute motion with respect to the ether.

The very great speed with which light is propagated, however, makes these differences, which depend upon the square of the velocity of light, extremely minute. Nevertheless they should be measurable, just as the parallaxes of the stars are measurable. Very difficult, to be sure, but still measurable. Michelson tried the experiment of measuring the motion of the earth relative to the ether with his newly invented interferometer, but the results were negative. The expected phenomena did not appear. He could find nothing to measure. Others tried similar experiments, but the results were the same; nothing that was expected appeared. It was a great blow to the theory, and the mathematical physicists were in great distress.

A few years later Fitzgerald and Lorentz showed that these failures could be accounted for by supposing

that all bodies moving through the ether contracted by an extremely small amount in the direction of the motion, the amount of the contraction varying as the square of the velocity of the body (about two and one half inches for the diameter of the earth), but the suggestion seemed artificial and it did not satisfy. It seemed that the electro-magnetic equations, like the gravitational equations, should be independent of uniform motion with respect to the ether. Larmor and Lorentz succeeded in finding a transformation which did leave the equations unaltered, but it was less simple than the transformation required for a body moving uniformly in a straight line, in that it transformed not merely the position of the body but its time also. In this way was introduced the concept of a "local fictitious time", and relative to this local fictitious time the electromagnetic equations actually are invariant. The local fictitious time depends upon how fast the body moves with respect to the ether.

It was at this point that Einstein appeared with the remark that this local fictitious time was the only kind of time we know anything about. In fact, it was actually our real time, and what we had previously regarded as real time was actually the fictitious time. This remark inverted the problem. Relative to Newtonian time, the gravitational equations were invariant while the electro-magnetic equations were not. Relative to Einstein's time, the electro-magnetic equations are invariant while the gravitational equations are not. The pinch of the shoe was transferred from one foot to the other, and Einstein boldly followed up the consequences.

In the special theory of relativity which followed, Einstein was interested only in the electro-magnetic equations Not only were the experiments of Michelson and Morley accounted for by this new point of view, but several other results that previously had been explained with difficulty were now explained very simply and no new difficulties of a measurable character were encountered. But it played havoc with the fundamental concepts of the entire human race. Time is no longer a public matter, the same for all, but is a private, personal matter Your time and my time are different, just as your personality and my personality are different. Two events, one in New York and one in Chicago, are simultaneous in my time, but if you are moving with respect to me these two events will not be simultaneous in your time. The speeds of two bodies which are moving in the same straight line are *not additive. For example, if you are riding on a train* which is moving relative to the track at a speed of 36 miles per hour and you are walking forward on the train with a speed of four miles per hour, your speed relative to the track will not be 40 miles per hour, but will be something less than that. A beam of light travels with a speed of 186,000 miles per second relative to its source. A normally-minded man would say that if two beams of light are travelling in opposite directions the speed of each relative to the other is twice 186,000 miles, but the relativist replies: "No! it is only 186,000 miles. It is just the same as though one of them stood still. A speed greater than the speed of light is impossible."

You and I regard a five pound mass as a five pound

mass for everyone. To the relativist that is not so. It depends upon whether you are standing still or running If you run fast enough it will be a ten pound mass, and if your speed is that of light, its mass will be infinite. Furthermore, there exists a definite relationship between mass and energy—namely, one gram of matter is equivalent to the square of the velocity of light ergs of energy.

It requires a great deal of courage to talk like this to sane people, but nevertheless these are the logical consequences of Einstein's postulates. Of course, the meaning of the word "time" has slipped a bit and the meanings of the other words have slipped with it so that it is not quite fair to make these statements to an unsophisticated person But if you can change your notion of time and make the corresponding change in the meanings of the other words it will be found that the statements are correct You will observe that it is like translating English into Russian. It doesn't sound quite right in Russian, but as usual that is because we do not clearly comprehend the meanings of the words

Einstein's special relativity ignored the fact that these new concepts were upsetting the equations of gravitation. People were so busy trying to learn this new language that they forgot all about this fact, or perhaps they never perceived it. But Einstein neither overlooked it, nor forgot it. He was meditating, trying to enlarge his notions so that both systems of equations should be independent of the reference system. Other mathematicians came to his assistance and in the geometry of Riemann and the calculus of tensors of

Ricci and Levi-Civita, together with a postulate of his own, which he called the Principle of Equivalence, to the effect that a gravitational field of force is indistinguishable from any other kind of field of force, he found the means of formulating his problem. The law of gravitation which emerges is not quite that of Newton, and a great variety of laws is possible. To all of them Newton's law is an extremely close approximation so that these laws give results in our own solar system which are indistinguishable from those of Newton except in one place, namely, the motion of the perihelion of Mercury. The law which is usually used was first given by Schwarzschild and it indicates an advance in the perihelion of Mercury of 43″ of arc per century greater than that indicated by Newton's law. Now it happens that there were two small discrepancies between the implications of the Newtonian theory and the observations. One of these is a slight irregularity in the motion of the moon, and the other is that the perihelion of Mercury is advancing 43″ per century faster than the theory indicated. Einstein's theory would explain one of these, and the explanation is incredibly perfect, but not the other. There are several other suspected discrepancies, but they are so small that they cannot be discussed with any certainty. That Eintein's law of gravitation should fit one of these discrepancies so perfectly and ignore the others altogether is a bit puzzling. But naturally the relativists seize upon this one agreement as a striking confirmation of their procedure.

There are other predictions which the new theory makes. A ray of light passing close to the edge of the

sun should be deflected from its straight line course by a definite amount. A careful test of this prediction was made by the Lick observatory and the prediction was confirmed. Another prediction was that the lines of the spectrum coming from a large body like the sun should be shifted towards the red, and this, too, after much trouble, has been affirmed by St. John at the Mount Wilson observatory where the instrumental equipment is of the very best. Thus the three predictions originally made by Einstein have been affirmed, at least roughly. Naturally the relativists are elated, and I think they have a right to be. In addition to these three definite predictions of Einstein the theory of relativity applied to the Bohr atom has been useful in interpreting the fine structure of certain lines in the spectrum, and possibly in other places. These successes of the theory have made some of the followers of Einstein over confident, sometimes even arrogant and irritating in their assumption of lofty superiority. A certain measure of success can be freely granted to the doctrine without for a moment assenting to the philosophy which underlies it, and I think it has been very successful in making mathematical formulas.

It will be granted, I think, that the law of gravitation has been very successful in the making of formulas. Indeed, it has always been regarded as the best verified of all physical laws, and it was not *invented* by Newton. The idea was current in Newton's time that the law of gravitation is the inverse square law because gravitation was supposed to be something like radiation and the law of radiation is obviously the inverse square law. Newton deduced the law from Kepler's

three laws of planetary motion and showed that it is equally applicable to the motion of the moon. He stated it in its present form, and so it is naturally called Newton's law. The underlying concept of radiation which first gave mathematical form to its expression was abandoned even by Newton himself. The formulas derived from it, however, remain as accurate and useful as ever.

Newton was able to explain many of the properties of light on the hypothesis that light consists of minute corpuscles which are emitted by the luminous body. But a hundred years later, Young and Fresnel succeeded in explaining the same phenomena and many new ones on the hypothesis that light is a wave motion in the ether. So numerous and so successful were these explanations that it became almost a dogma that light is a wave motion in the ether. But the recent work of Compton and others has brought into evidence phenomena that can not, apparently, be explained by the wave theory.

The electro-magnetic theory was based upon the concept of an ether, and it is the relativists themselves who put the ether into the discard This is one of the defects of the doctrine of relativity, for it does not say anything about how light is propagated. Both the emission theory and the wave theory give clear notions on this point. They may not be adequate, but the doctrine of relativity gives us nothing at all.

In the second century A. D. the astronomer Ptolemy in writing his book, the Almagest, which was the bible of the astronomers for fifteen hundred years, was called upon to decide between the geocentric and the

heliocentric theories of the solar system. Both theories were well known, but Ptolemy decided against the heliocentric theory, which has been the standard theory for the past three hundred years, because he could observe no parallax for the fixed stars. If the earth moves around the sun there should be a relative displacement of the stars among themselves with a period of one year. Since he could find no evidence of such a displacement, he concluded that the earth is stationary and that the sun moves around the earth. Fifteen hundred years later the telescope was invented and with this powerful addition to their equipment the search for the parallax was renewed, but again no parallax could be detected. More than two hundred years passed away before their search was rewarded. A star does have a parallax after all. But how different is the scale of the sidereal universe from that which Ptolemy had anticipated.

In the days of Newton the parallax had not yet been found. Suppose Newton in constructing his dynamics had made it a postulate that the parallax did not exist, and suppose further that he had succeeded in building up a Celestial Mechanics in which the earth was at rest relative to the stars. How much more complicated would such a system of mechanics have been, than if he had proceeded, as he did do, by ignoring the parallax altogether, and had followed his intuitions with respect to time and space and force. It was just one hundred and fifty years after Newton published the Principia that the parallax of the stars fitted into his scheme as a matter of direct evidence.

We of the present generation are too impatient

to wait for anything. Within thirty years of Michelson's failure to detect the expected motion of the earth with respect to the ether we have wiped out the slate, made a postulate that by no means whatever can the thing be done, and constructed a non-Newtonian mechanics to fit the postulate. The success which has been attained is a marvelous tribute to our intellectual activity and our ingenuity, but I am not so sure with respect to our judgment. Our normal mode of procedure is to assume that a certain something is true or to guess that a certain thing can be done, and then to test our assumptions and guesses by experience. I think I am safe in saying that the vast majority of our hypotheses find their way promptly to the waste basket and are forgotten. Occasionally one is found that meets with a certain measure of success and we are elated with it, only to find later that it won't do and it is laid aside with regret. On rare occasions one is found, like Newton's law of gravitation, or the electromagnetic theory, that seems to be a permanent acquisition of the race. But there are grave difficulties even with the best of them. I think I am also safe in saying that no physical hypothesis will do more than harmonize approximately our system of postulates and our experience, or, to use more popular language, no physical hypothesis is more than an approximation to the truth. Nature is infinitely complex and therefore we have only to push our experience far enough to find that our physical laws are imperfectly stated, and that our physical models are inadequate.

It is not our normal mode of procedure to assume, after two or three failures, that by no means whatever

can the thing be done. It is particularly distasteful to do so when such an assumption involves the conclusion that our experience can no longer be interpreted in terms of the time and space of our intuitions, and that we have accordingly reached the limits of what is intelligible.

The notion of simultaneity in two distant places according to Newtonian mechanics is not ambiguous, as is so frequently asserted by the relativists. We can set two distant clocks to indicate the same time with a certain margin of error. That there is a lower limit to this error merely asserts that our intellects are more delicate than our physical apparatus. However fast or slow light may go, we can imagine a speed a million times as great, or any other ratio that may be desired, and there is no lower limit, save zero itself, to the determination of simultaneous events so far as the mind is concerned. To say that simultaneity does not exist because it is unattainable in practice is like saying that a straight line does not exist because it, too, physically is unattainable. Shall we then put geometry into the discard because it is ambiguous and without meaning? If we do the matter is ended, for there is nothing left for us to talk about.

The process of idealization is a fundamental process in all of our thought. Our ideals are the norms in terms of which we think and without them there will be no thought at all. Some set of ideals is indispensable. So far as I can see our normal set of ideals, which include Euclidian space and Newtonian time, is not an exclusive one. Other sets are possible, perhaps infinitely many, but I can see no reason for

believing that some other set is better than the one with which nature has endowed us. As the non-Euclidian geometries of Riemann and the non-Newtonian mechanics of Einstein, which is merely a non-Euclidian geometry in four dimensions, clearly show, we can trace the application of these ideals by the rigid processes of logic, but our intuitions, which are the eyes of all our thoughts, are blind, and I am sure that we shall not go very far without our eyes. So far as I can see, such schemes are entirely possible, but I feel quite sure that they are futile. The relativists have gathered a few flowers in the dark, but I am afraid we shall wait a long time before they have gathered an armful.

It will be observed that in the preceding discussion I have granted all of the claims of the relativists, and still I have denied their conclusion that the relativists are the sole dispensers of the truth and that we must all become relativists. The situation is something like that of a boy and his bed clothes. The boy grew but the bedclothes did not. All at once the boy discovered that his little toes were sticking out from under the covers and he was decidedly uncomfortable. Try as he would the bedclothes could not be stretched far enough to cover them up. Suddenly he had a bright idea. All he had to do was to slip the entire bed covers down six inches. His feet went under beautifully and he was so happy about it that it took him some time to discover that now his neck was uncovered and that he had merely shifted the seat of the difficulty for the bedclothes were no longer than they were before. The relativists have succeeded in covering up the little terms of order two, but in doing so they have robbed

us of all ideas as to how light is propagated in space, and that problem is even more important than the little difficulties at the other extremity.

The experimental evidence, however, upon which the relativists have laid so much stress, is not so clear as one might wish. In granting that the evidence is all that the relativists could wish it to be I have granted too much. This part of the discussion will be taken up by Professor Hufford who will show that the evidence is very obscure. To me, however, the evidence is not a decisive matter. It is quite likely that each of the two schemes can be modified so as to cover the evidence, whatever it may be. If this estimate is correct, the mechanics of Einstein will, from a philosophical and a historical point of view, occupy a position beside the geometry of Lobachevski, and the human race will continue, as before, to think in terms of Euclidian space and Newtonian time.

IS THE EXPERIMENTAL EVIDENCE OF RELATIVITY CONCLUSIVE?

The Second Speech of the Negative by Professor M. E. Hufford.

In surveying the progress of physics during the last century one is impressed by the method of its growth. The first step is the statement of a principle or hypothesis more or less new in departure, and the second step is a searching experimental investigation of the truth or falsity of the theoretical statement. At the present time we have before us the theory of relativity, still, in the estimation of most physicists, in the theoretical stage. It is true some observations and experiments have been made and important ones are sure to follow. However, many experimental physicists feel that our investigations in the laboratory are too few and our astronomical observations far too limited to prove and establish relativity fully.

It is my purpose to discuss the so-called experimental triumphs of the theory of relativity and to point out some instances wherein these fall short of proof. It is an occasion also to point out other requirements which the theory must meet in order to take its place along with those great principles like the wave theory of light, the theory of the electron constitution of atoms and others which are the substantial framework of science.

At the outset it is clear that relativity is very closely

associated with the theories of light. In fact the hypotheses of relativity arose in an effort to account for a difference between theory and experiment in that field. Let us consider briefly, therefore, some important advances in the concepts which underlie that subject which were made in the years between 1675 and 1750. This was one of the most important periods in the history of physics for during this time the foundations of our present day ideas of the nature of light and the manner of its passage through space were laid. In 1675 Newton communicated his theory of the corpuscular nature of light in which he encountered the difficulty of accounting for the gradual reduction in intensity at the edge of shadows. Huyghens in 1690 accounted for the bending of light by assuming a wave method of propagation. Roemer, just before this period, had satisfactorily proved that light does not have an *infinite* velocity and in 1728 Bradley made his celebrated observations on the angle of aberration of the fixed stars. Since the Bradley experiment is the starting point for the situation in which physics found itself at the time of the announcement of the Einstein theory we may stop a moment to consider it.

If a ball thrower should throw a ball toward a moving railway car in which the windows were open, it is possible to imagine that the speeds of the car and the ball might be such that the ball could enter the front window on one side and pass out at the last window on the opposite side. Now a passenger on the car and the thrower would disagree as to the direction in which the ball actually moved. The passenger would certainly maintain that the ball was thrown in a

direction diagonally across the car. In the case of the Bradley experiment the observer corresponds to the passenger and if he is to direct his telescope so that light from a star is to pass down the axis of the tube he must point his instrument ahead of a straight line connecting himself and the distant star. Six months later, when the earth is moving in the opposite direction in its orbit, he must direct his telescope at the same angle in the opposite direction. It is easily seen that the ratio of the velocity of light to the velocity of the orbital motion is the tangent of the angle of aberration. Bradley and astronomers until recent years have accounted for the results of this experiment on the basis of a stationary or, as we customarily say, a stagnant ether.

Now all went well until new phenomena were discovered and then arose the conflict which today we are attempting to explain by relativity. The phenomena referred to were those involving a slowing up of the velocity of light in media which are denser than air and the fact that blue light suffers greater decrease in velocity than the red. Fresnel offered as an explanation of these phenomena the idea that the ether in matter is denser than the free ether. It is easy to see, therefore, that if the Bradley telescope tube were filled with water the angle of aberration should be increased.

This experiment was tried by Airy and Hoek and strange to say the angle of aberration was not changed. Of course it is possible that the matter filling the tube may drag the ether along with it just enough so that the velocity change by altered density of the ether is just compensated for. This gives rise to an ether-drag

theory. Fresnel derived a law in which the velocity, u', of the ether, that is the drag velocity, in relation to the velocity u of dragging matter, was expressed by the formula:

$$u' = \left(1 - \frac{1}{n^2}\right) u.$$

The Airy-Hoek experiment required, then, that the ether filling the tube have greater density than that outside and that either the ether inside is permanently attached to the tube and that tube and all move through the free ether like a tube filled with jelly moves through a basin of water, or else that the ether

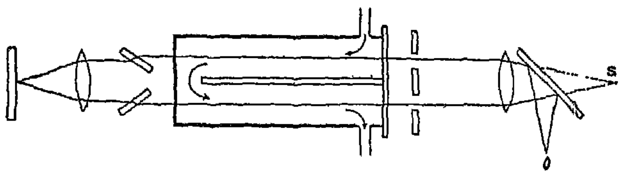

Figure 1.

flows in at one side and out at the other crossing the tube with a speed less than that of the tube.

In 1859 Fizeau in France devised an experiment to test the law of the drift of the ether with matter which had been proposed by Fresnel. As shown in Figure 1, light from a source S fell upon a mirror set at 45°. From the mirror two beams of light passed through a lens, thence through apertures and through a water-filled tube. Another lens and mirror then caused the light beams to return through the tube, the paths being interchanged. It will be seen that the one beam traveled through the water in both directions with the flow of water, while the other moved against the

stream. At the point of observation the crests and troughs of the light waves of the two beams came together in such a way that a system of interference bands was produced. Now when one of the beams was retarded over the other the whole system of bands move across the field of view. The arrangement was an exceedingly delicate one, and by it Fizeau found that when the speed of water reached two meters per second he could observe the shift while with seven meters per second he could measure it. This experiment was repeated by Michelson and Morley at Cleveland in 1886 with precisely the same results. Apparently the correct conclusion to be drawn from the experiment is that an ether exists and that transparent matter carries the ether with it to a measurable extent.

Fresnel's theory also supposes that the ether outside of transparent bodies remains stagnant. To test this part of the theory was the aim of Michelson and Morley in their work published in 1887. This is the experimental work known as the Michelson-Morley experiment. It was Einstein's effort to explain the negative result obtained which in part gave rise to relativity.

Light from a source S in Figure 2 was divided by a mirror set at an angle of 45°. The two beams traveled over paths D and D′ of an interferometer at right angles to each other. After retraversing the paths the light was reunited so that interference fringes were produced Any retardation of light in one path over that in the other was indicated by a shift of the fringe system. Since the velocity u of the earth in its orbit carries the apparatus forward as shown by the broken

lines, the effect is to increase the path D' over the path D by an amount $D\ u^2/c^2$ where c is the velocity of light. When the apparatus is rotated through 90° the effec-

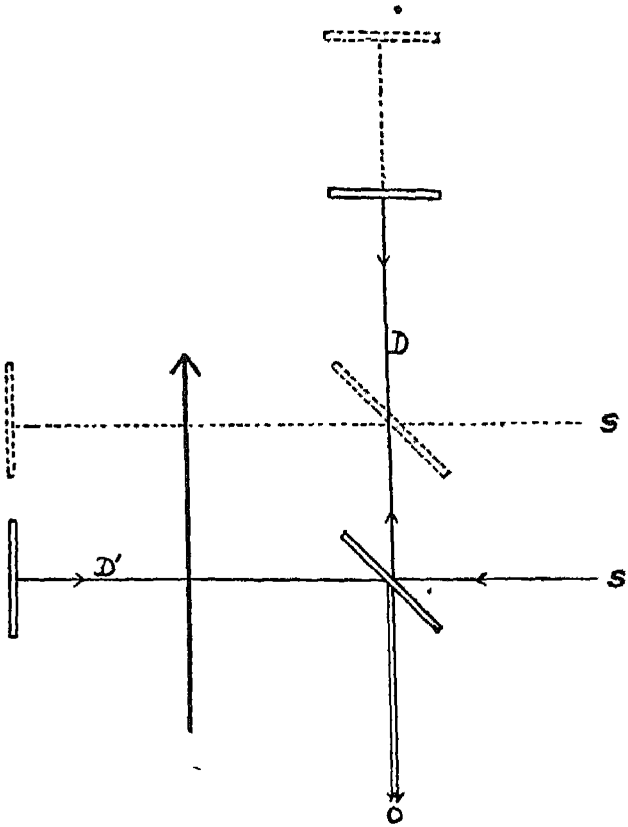

Figure 2.

tive difference in path is doubled. Michelson and Morley predicted a fringe shift of 0.4 of a band, but

the experiment yielded less than 1/20th of a band. The Michelson-Morley experiment may be interpreted, therefore, as showing that, contrary to Fresnel's hypothesis, the ether is carried along with the earth with a velocity between 3/4 and 5/6ths of the earth's velocity.

Due to the importance of the experiment as deciding against a fixed ether which so well explained the Bradley experiment, Lord Kelvin at the Congress of Physics at Paris in 1900 suggested that the experiment should be repeated with still more sensitive apparatus. This Morley and Miller undertook to do in 1904 and 1905. The fringe shift expected with improved apparatus was 1.5 bands. These experimenters announced as a result of the repetition, that if the ether moves past the earth it is with a velocity less than 3.5 kilometer per second; that is, the ether is carried along with 7/8 or 9/10th of the earth's orbital velocity.

Not completely satisfied that the small positive result was due to experimental error, Miller in 1921 to 1925 has repeated the experiment at Mount Wilson and again at Cleveland. The reason for choosing Mount Wilson, where the elevation is 6,000 feet above sea level, was to see whether or not there is greater relative motion of the ether at greater distances from the surface of the earth. In all, 12,500 determinations have been made. The apparatus was used in such a way that a minimum fringe shift indicated the direction of the resultant motion of the earth in space and the maximum shift indicated the magnitude of the relative motion of the earth and ether. The measurements have been grouped so that all the data of a group have the

same conditions as regards the known motions of the earth.

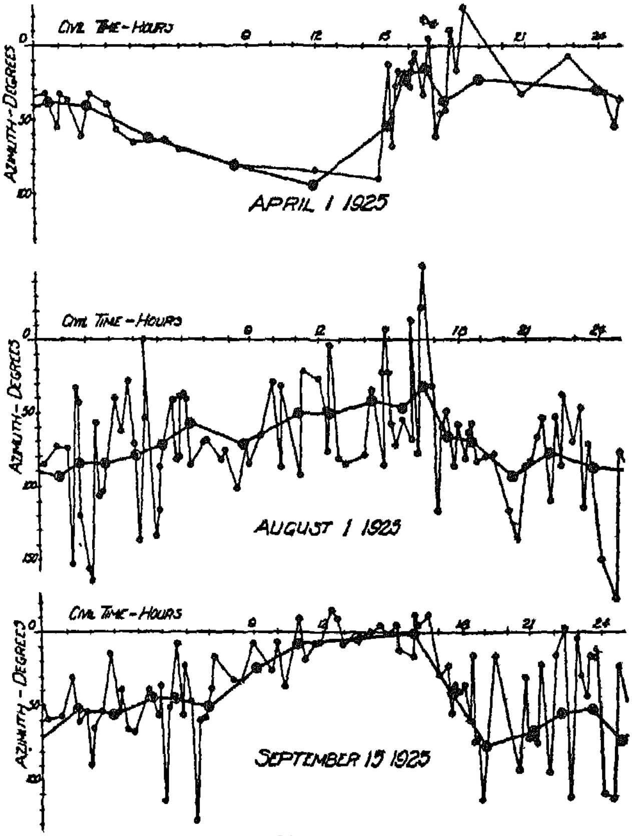

Figure 3.
From D. C. Miller in Science.

The curves of Figure 3 show the results of measurements made during 1925 on the direction of the

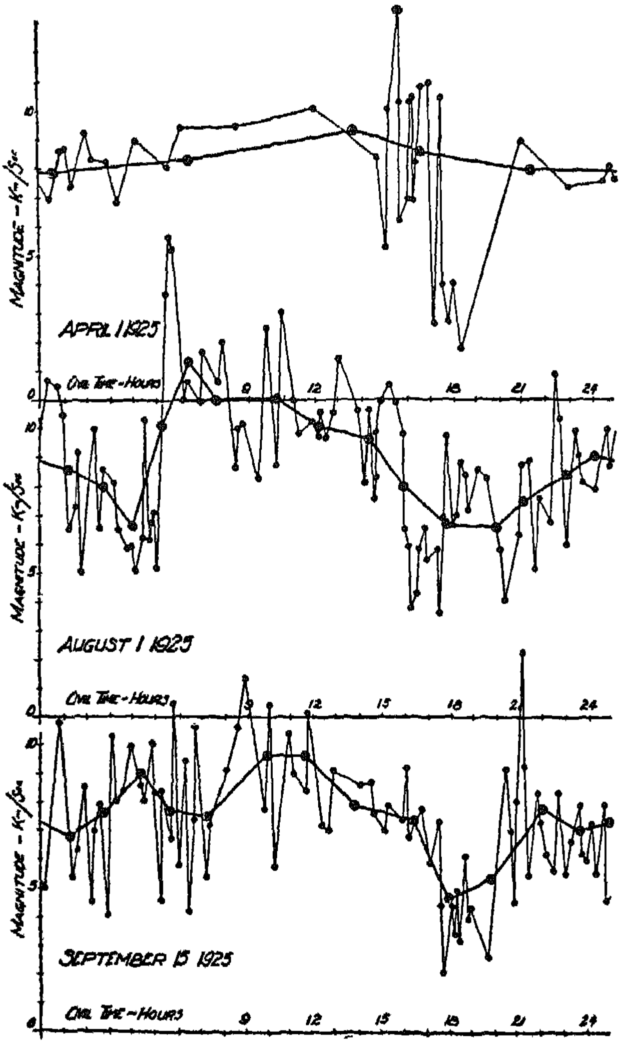

Figure 4.
From D. C. Miller in Science.

relative motion. While the earth remained approximately at a given position in its orbit, that is during a day, the apparatus was rotated as much as 20 turns per hour and the direction in which a minimum fringe shift occurred was noted. The ordinates of the small dots of the curves represent the angle at which a minimum occurred. The heavy line represents average angles. The curves of Figure 4 show the relative motion of the earth and ether as calculated from the maximum fringe shift Here the ordinates represent kilometers

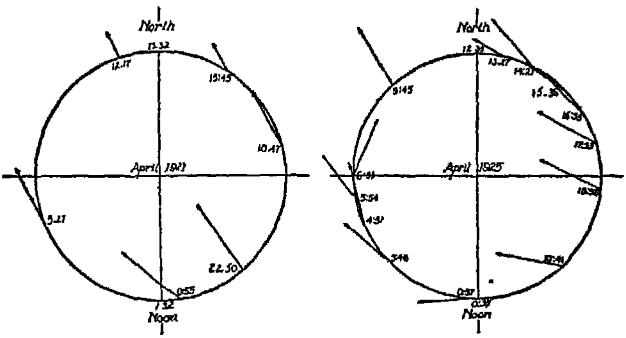

Figure 5.
From Proceedings of the National Academy of Sciences.

per second of difference of velocity of the earth and ether. While there is considerable variation it is clear that a definite drift velocity is indicated.

These same results are shown in another way in Figure 5. Here the circumference of the circle represents a sidereal day. The magnitudes of the ether-drift values determined at different hours of the day are represented by the lengths of the arrows and the directions of the arrows indicate the direction of the

drift. While the results of 1925 show more variation of direction still it is clear that there is a general drift toward the north west. The fact that the results of the two periods agree inspires our confidence and we must

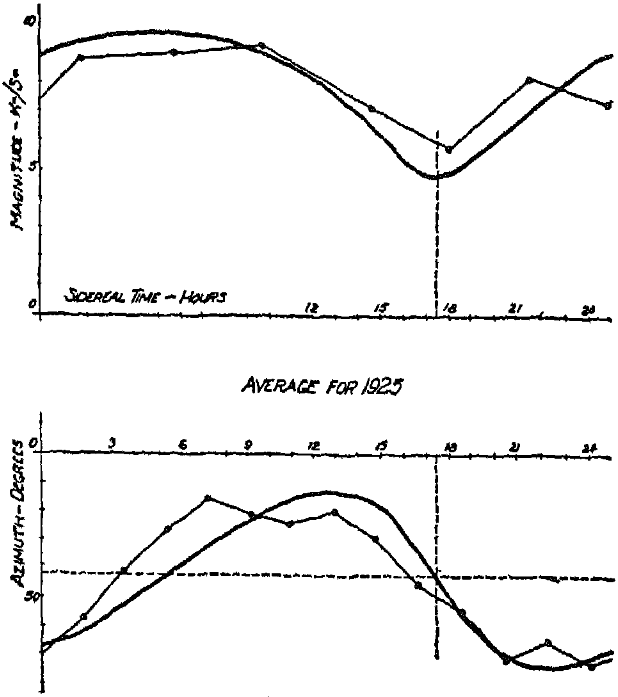

Figure 6
From D. C. Miller in Science.

admit that Miller has found a definite velocity of drift.

Miller made a careful search for a direction and magnitude of motion of our solar system which, when compounded with the known revolution and ro-

tation of the earth and projected upon the plane of the interferometer would give a curve representing magnitude and direction like Figures 3 and 4 obtained by experiment. It has been found that an assumed resultant drift motion in the direction of the constellation Draco of magnitude ten kilometers per second, gives projections which agree remarkably well with experiment. The curves of figure 6 show this agreement. The light-line curve represents the general average of experimental results and the heavy-line curve represents assumed magnitudes and directions. In all of Miller's experimental work he found that the earth's orbital motion is without effect on the results. If, therefore, it is assumed that the earth's orbital motion is a component of the drift velocity which is just below the limit of the resolving power of the interferometer, then in order to obtain the drift velocity of ten kilometers per second, which is only a residue, so to speak, of the true velocity in space that is masked by the large drag of the ether by the earth, the other component of motion must be a velocity of 200 kilometers or more per second in the direction of the constellation Draco.

It does not seem possible to attribute any of these results to experimental or other errors. In taking the data every precaution was used to remove the errors which might be caused by the mechanical disturbances, heat effects and magnetic effects. Mirrors were changed, observers were shifted about, even the building was moved and differently oriented.

These results are, therefore, a serious challenge to the theory of relativity, because in that theory one of the postulates is that the velocity of light in free

space is constant and is independent of whether we assume the presence of an ether or not. It should be pointed out, also, that one of the important conclusions of relativity is that, whether the ether is assumed to exist or not and whether it is stagnant, drifts, or is carried along, it is not possible to detect any motion of the earth in space by means of light.

The experimental physicists now leave it to those theorists, who accounted for a supposed null result of the Michelson-Morley experiment by relativity, to see whether that theory can satisfactorily account for Miller's results. The challenge is a serious one to those who have faith in relativity. The outcome will mark an epoch in science.

I wish to discuss another experiment which has been regarded by some mathematicians and physicists as a complete verification of the theory of relativity. In an effort to explain the null result of experiments like the Michelson-Morley experiment, FitzGerald first proposed that material bodies, when in motion, actually diminished in size in the direction of their motion. Einstein has introduced into his theory certain postulates which, when followed to their logical conclusions, also lead to this same principle. Accordingly we have the expressions:

$$m_l = \frac{m_o}{1-\beta^2}\ , \text{ and } m_t = \frac{m_o}{\sqrt{1-\beta^2}}\ ,$$

where m_o represents the mass of the body when at rest, m_l the mass when it is moving parallel to the relative velocity of the two systems, one of which contains the moving body and the other the observer; m_t

represents the mass when the motion of the body is at right angles to the relative motion of the systems; β is the ratio of the relative velocity of the systems to the velocity of light. From these formulas it is clear that the mass of a body is larger when it is in motion than when it is at rest. The expressions also say that if the speed of the body becomes equal to that of light its mass becomes infinitely great.

This change of mass with velocity was tested in the Kauffman-Bucherer experiment. The apparatus consisted of parallel circular plates A and B, Figure 7, placed very close together. At X a small amount of radium fluoride ejected electrons whose speeds were nearly that of light. Electrons spread out in all di-

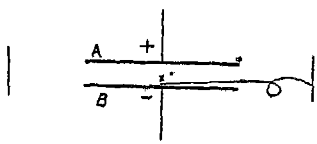

Figure 7.

rections and fell on a circular film which completely surrounded the plates at some distance from them. The impression of the electrons on the film made a black line. Then, with an electric field perpendicular to the plates and a magnetic field in the plane of the plates, the high speed electrons were caused to travel over a spiral path between the edge of the plate and the film. If, then, the mass of an electron, due to its speed, is so great that it is not deflected by the magnetic field, and the value of $\beta = \frac{\text{velocity of the electron}}{\text{velocity of light}} = 1$, it is found from simple calculation that the traces of the electrons with field on and field off should coincide at

positions around the film 180° apart. A maximum difference should be shown at points half way between. Figure 8 is a reproduction of the photograph obtained in this way.

While the result of the experiment is very beautiful, indeed, we are impelled to examine the assumptions. We can arrive at exactly the same form of equations as those just mentioned if we assume, instead of a variation in mass, a variation of the charge of electricity carried by the electron. In fact, one of the postulates of relativity states that the sum total of electricity in any isolated system remains unaltered. We have a right to question the truth of this postulate, and we can

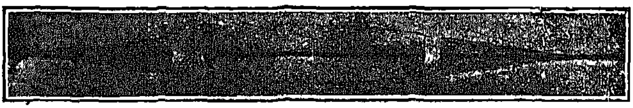

Figure 8.
From A. H Bucherer, Annalen der Physik

not conclude that relativity has been established until we have established the truth of this statement by experiment. This may be a difficult problem for we measure charge only by its effects and it is conceivable that the medium of transfer of the effect might be subject to change with a variation of the velocity of the charge. In a recent paper by Bush,[1] it has been shown that all of the relativity equations result from an assumption of constant mass and changing charge just as we now have them by postulating a variable mass and a constant charge. It has been stated by one

[1] *Bulletin of Massachusetts Institute of Technology,* vol 5, No. 3, p. 129.

of the ablest mathematical supporters of relativity that if the relation

$$e_t = e_o\sqrt{1-\beta^2}$$

is found for charge, the whole theory of relativity will be overturned, and if any relation, except a constancy of charge, is found the theory must undergo modification.[2]

[2]R. D. Carmichael: *The Theory of Relativity*, second ed., (1920), p. 70.

Let us turn attention now to another of the so-called proofs of the Einstein theory. This is the advancement of the perihelion of the planet Mercury. It is well known that the orbits of the planets are ellipses. That portion of the ellipse nearest the sun is called the perihelion. It has been observed that the orbit of Mercury slowly rotates about the sun. Leverrier computed the path of Mercury, taking account of the attractions of the earth, Venus, Jupiter and three other bodies. He found that the actual and calculated motions failed to agree by an amount which would be nearly 38 seconds of arc per century. Leverrier could not understand this discrepancy and suggested that there might be unknown masses of matter near the sun. Since that time some matter has been found and exactly where Leverrier predicted that it should be. In 1895 Newcomb repeated the calculation and by slightly reducing the eccentricity of the orbit he slightly increased the rotation and obtained 41 seconds per century.

Now Einstein by the use of the equations of relativity has calculated that the perihelion of Mercury should rotate 43 seconds per century due to the supposed change in space and time in the neighborhood of

the mass of the sun. It has been pointed out by Professor Poor that, in making these calculations, Einstein failed to use his relativity unit of time, but used instead our constant Newtonian unit of time. The agreement between the calculated values of Leverrier and Newcomb on the one hand, and of Einstein on the other has been considered definite proof of relativity. But it must be remembered that Newcomb was forced to guess the density of Mercury and the other planets. Hence the figure 41 may be far in error. Since the so-called verification by the calculations of Einstein, the rotation of the perihelion of Mercury has been recalculated and values of 33 and 29 have been announced. We have here a variation of 27 per cent.

In a recent issue of the Proceedings of the Physical Society of London, J. T. Combridge[3] has a mathematical paper on the shift of the perihelion of Mercury. In that paper it is shown that if we take the equations of Newtonian mechanics and add a potential function, we can get the Einstein equation for the orbit of a planet. This yields possibilities of explaining the shift of the perihelion of Mercury as well as the bending of rays of light by the sun without resort to the Einstein postulates and equations at all. The author states that there are endless possibilites of "explaining" the "crucial" phenomena of Einstein's theory without appeal to that theory. It is pointed out in the paper that the motion of the perihelion of Mercury depends upon only one of the ten coefficients in Einstein's quadratic form. We need, therefore, for a crucial test as between Ein-

[3]*Proceedings London Physical Society*, vol. 38, (1926), p. 161.

stein's theory and the Newtonian equations with an added potential function, a phenomenon which involves more than one of the coefficients. We must have a wider search for further possibilities of experimental investigation.

Another observation which has been considered a triumph for relativity is the bending of a ray of light which passes near a massive body. By assuming a strained condition in space accompanying a localization of energy and that these strains experience resistance when in motion, it is concluded that energy and mass are one and the same thing. Light energy is, on these assumptions, subject to the gravitational action. If, therefore, a beam of light passes close to the sun's limb, it should be attracted by the sun and its path curved. Substitution of values in the relativity equations shows that the maximum bending of beams from stars seen just at the edge of the sun should be 1.75 seconds of arc. Of course to make measurements of the displacement it is necessary to utilize the few minutes during a solar eclipse. Two opportunities for such observations have occurred. Observations were made by British astronomers who were sent on an expedition to South Africa in 1919 and the Lick observatory sent an expedition to Australia in 1922. Both parties brought back positive results. These results have been accepted by relativists as a complete verification of their theory.

But in examining the conditions of the observations and the results, one wonders whether the proof is so complete. In the first place, both Professor Eddington who headed the British party and Professor Camp-

bell who was in charge of the American group are enthusiastic relativists and one must wonder whether they approached their problem with entirely unbiased minds. In the second place it has been shown that 0.87 seconds deflection, that is half of the computed amount, should be expected on the basis of the Newtonian corpuscular theory.

Since the advent of Planck's quantum theory of energy a great deal of interest has been restored to the Newtonian corpuscular theory. Sir J. J. Thomson during the past year has published several papers in which he has attempted to credit the corpuscular theory, that is, the quantum theory, along with the wave theory of light. According to Thomson's view a part of our light energy exists in the form of waves, while another part exists in the form of corpuscles or light quanta. Here again we need more experimentation

But even on the basis of the wave theory we should expect a bending of light both at the surface of the sun and again when a beam enters our own atmosphere. This is the ordinary refraction phenomenon. We know something about the refractive properties of the lower layers of our own atmosphere, but we know much less about the rare upper layers and still less about the dense layers of atmosphere of the sun. To be able to say just how much a beam of light, which is of magnetic and electric nature, should be bent in passing through a very intensely hot atmosphere composeu of very heavy gases and vapors, ionized and un-ionized, attracted by a body of great mass surrounded by strong gravitational and magnetic fields, is, indeed, difficult. It must be remembered, too, that when our earth passes

into the shadow of the moon, as it does during an eclipse, when our bending measurements are made, our atmosphere suffers great cooling and, therefore, contraction and change of density. These changes are sure to be accompanied by changes in refraction. Also when radiation from the sun is cut off our atmosphere loses its ionized state in the upper layers. With all of these changes the problem of understanding the bending of the sun's rays during eclipse is, indeed, difficult.

The apparent displacements due to bending of light by the sun, as computed on the basis of relativity, are shown in Figure 9. The photograph is from a drawing by Professor Poor. Figure 10 is a photograph of a drawing of the actual displacements of the stars by Professor Poor. These displacements were made from the data of the Lick observatory astronomers. In both of these photographs, one theoretical and the other from the data of observation, Professor Poor has multiplied the displacements by a given constant factor. It will be observed that in some cases the bending near the sun was far less than was expected and some of the beams farther out are bent far too much. Fifteen of the star images show bending in the predicted direction and twenty-six show a deviation exactly opposite to that required by relativity. Out of these complicated displacements Professor Campbell deduced results and announced 1.72 seconds as the observed displacement. A re-calculation, however, showed 2.05 seconds. This is a 17 per cent variation from the amount predicted. No experimental observation can be regarded as decisive with such a large difference as this, and especially

when the difficulties of observation and the extremely limited time are taken into account.

Within a few years we have heard much about the verification of relativity by the shift of the lines toward the red region in the spectrum of the light from a massive body. Such a shift is predicted on the basis of slower time on a large mass accompanied by lower frequency of oscillation of electrons in producing light. With slower vibrations the corresponding spectrum lines appear farther toward the red. This is an effect like that produced by a source rapidly moving away from an observer, thus increasing the wave length of the light. A shift produced by motion is a Doppler effect. Now Einstein's equations show that the mass of the sun should produce an increase in the wave length of light equal to .008 of an Angstrom unit, that is 8×10^{-11} cm. increase over the same wave of light on the earth. Attempts to measure this very small shift have proved unsatisfactory. At the suggestion of Professor Eddington attention has, therefore, been directed toward the much denser faint companion star of Sirius. In Sirius and its companion we have a most interesting combination. We know the relative velocity of the two bodies. We know what to expect from the Doppler principle. The mass of the faint companion is equal to that of our sun. Spectrum analysis and absorption effects show that its temperature is 8,000°. The intrinsic brightness of the star is low although it is called the White Dwarf. This is interpreted as indicating small size. Hence the density as computed by Eddington is 50,000 times that of water. Our earth is 5.5 times that of water. With

these data the Einstein shift amounts to .3 Angstrom units, an amount well within the reach of our instruments.

At the meeting of the American Association for the Advancement of Science, at Kansas City, in January,

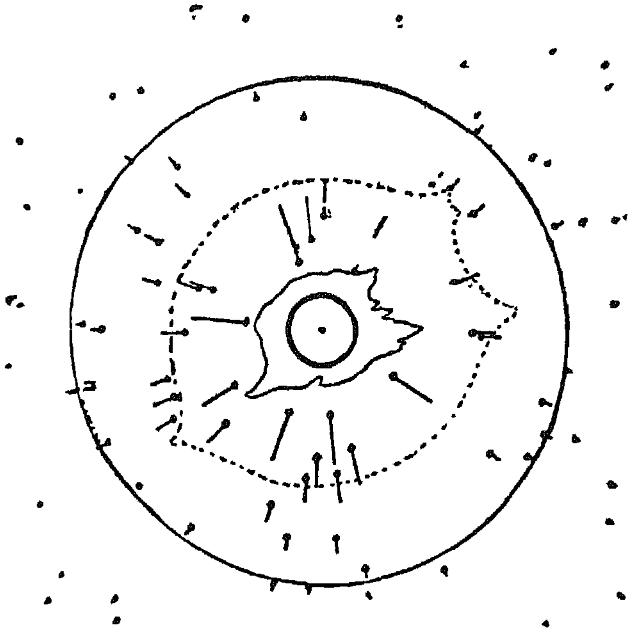

Figure 9.
From C. L. Poor in The Forum Magazine.

St. John from the Mount Wilson observatory showed photographs of the spectrum lines of light from the star Sirius and a comparison spectrum of the light from the faint companion. The shift of the lines in the latter spectrum was clearly shown and was of the

magnitude predicted by relativity.

It seems necessary to experimentalists in drawing a conclusion from observations like those given by St. John to take account of other possibilities which might explain the facts. In such a high temperature the

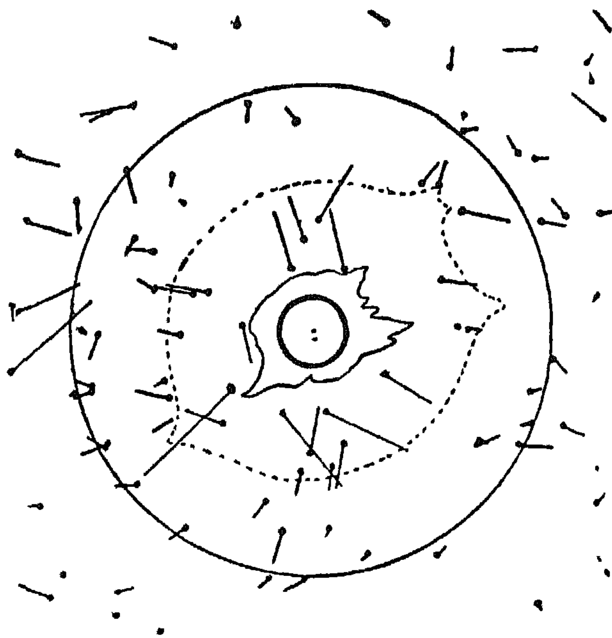

Figure 10.
From C. L. Poor in The Forum Magazine.

atoms concerned with the origin of the light must be broken up, that is, ionized singly, doubly, etc.; it would be difficult to tell to what extreme extent. There is a very heavy atmosphere about such a dense hot body. This would produce layers of gas and vapor which

would refract the light. There is probably also a strong magnetic field about the companion star. No one can tell what line-shift may occur when a source of light is placed in a region of such high temperature, great pressure and intense magnetic field Such conditions are most difficult and perhaps impossible to reproduce in the laboratory. There may, therefore, be other ways of accounting for this phenomenon than to say that the atomic vibrator is slowed up because it is placed on a massive body where time moves slower.

We have had a very interesting attempt at verification of relativity in an experiment undertaken on a large scale by Michelson and Gale near Chicago. In this experiment a twelve-inch pipe line a mile in length was laid in the form of a rectangle (See figure 11). By a system of pumps the air in this line could be reduced. Light was sent in at one corner of the rectangle. It was divided by a mirror and one beam was passed around the tube in one direction and the other around in the opposite direction. The two beams were brought together again in such a way that interference fringes were formed. Any change in velocity of the light due to the earth's orbital motion affects one of the light beams more than the other. This effect is indicated by a displacement of the interference fringe system. A fringe shift of .236 of the width of a band was expected on the basis of calculation. A fringe shift was obtained. Sometimes it was large, sometimes small. Out of a large number of very varied results an average value of .230 was deduced. The relativists claim this as a proof of their theory, but it has been shown

THE EXPERIMENTAL VERIFICATION OF RELATIVITY

Concluding Arguments of the Affirmative by Professor H. T. Davis

In the last analysis a physical theory must survive or perish at the hands of the experimenter. No matter how much it may appeal to our reason or stimulate our imagination the real test of whether it exists merely as a fancy of the mind or represents an interpretation of physical fact must come from the laboratory. Immanuel Kant has sought to reduce experience to a subjective basis and in doing this his space and time have become shadowy creations which forever elude us in the strange mystery of the source of *a priori* knowledge. There is something much more satisfying to the mind in referring the mystery of space and time to an objective reality in which knowledge is not already inherent in the mind, awaiting some slowly evolving revelation, but presents a challenge to experimental science. Ernst Mach, whose ideas on the relativity of motion were ahead of his time, has put it thus: "Mathematical and physiological research has shown that the space of experience is simply an *actual* case of many conceivable cases, about whose peculiar properties experience alone can instruct us."

I should like, first, to call your attention to an experiment that, for all its simplicity, nevertheless is one that has profound inplications. In 1852 Jean

Foucault hung in the pantheon at Paris a spherical pendulum and demonstrated that the axes of the ellipse described by the bob revolve around the vertical in the direction east-south-west-north with the angular velocity $\Omega \sin \phi$ where Ω is the angular velocity of the earth and ϕ is the latitude in which the experiment is performed. If the pendulum is set to swinging at the north pole the axes of the ellipse described by the bob will have the angular velocity of the earth as we measure it by reference to the external framework of the fixed stars, but if the pendulum is removed to the equator then no such motion can in any way be detected. How can we explain this experiment? It means this, that the pendulum can be used to detect an *absolute acceleration* of matter in space, but can never detect what we might think of as an *absolute velocity*. Every point in a plane tangent to the earth at the north pole and rigidly fixed to it is subject to an acceleration directed toward the pole, but on the equator every point in a tangent plane has a constant, that is to say, an unaccelerated velocity equal to 1500 feet per second. What Foucault's pendulum does is to detect the acceleration, while it leaves the velocity absolutely undiscovered.

In making these statements one should point out the rather curious fact that the absolute rotation of the earth corresponds within the limits of experimental error to its rotation as determined by referring to the framework of fixed stars. The space-time continuum in the neighborhood of the earth, however, is sufficiently different from the space-time in vacuo that a secondary effect should appear, according to Professor

Eddington, in the rotation as determined on the one hand by reference to the fixed stars and on the other by the Foucault pendulum. As the estimated effect is only 1.94″ per century this prediction is beyond the reach of experimental verification.

After we have reflected upon the very surprising fact that by no mechanical means can we detect an unaccelerated velocity, although accelerations even of small order are readily found, it does not require an unusual generalization to arrive at the principle that velocities are outside of our experimental range even when light pulses or any other physical phenomena are used to find them. For example, aberration tells us with great accuracy our orbital velocity, which like the velocity of rotation is an accelerated one, but gives no answer at all to the perplexing question of where and how fast we are travelling in space itself.

In an interesting paper on the subject L. Silberstein has considered the problem of "the Rotating Earth as a Reference System for Light Propagation" and has pointed out that one of the principal features of the theory of relativity is the close connection established between the behavior of mechanical and optical phenomena.[4] "In fact, ... whatever the quadratic differential form determining the metrical properties of a world domain, its geodesics prescribe the motion of the free particles, and the minimal lines of the *same metrical manifold* express the propagation of light in vacuo". The Michelson-Gale experiment, which will be described later, was devised to test the agreement of optical phenomena on the earth with this principle

[4]*Philosophical Magazine*, vol. 48 (1924), pp. 395-404.

It is interesting to observe that the discovery of the inertia of energy follows directly from this point of view, which is a simplification of physical principles that is greatly to be wished for.

In the light of these remarks the experimenter might, perhaps, postulate relativity like this:

I. Unaccelerated velocities are not absolute properties of physical bodies, but are derived from relative positions in space and time.

II. Accelerations are absolute properties of physical bodies and can be objectively determined.

I should like to refer next to an experiment which was performed a short time ago by Professor Michelson and Professor Gale of the University of Chicago.[5] A line of twelve-inch pipe something over a mile in length was laid near Chicago in the form indicated by the accompanying picture. The air was then pumped out until a vacuum was formed in which the air resistance was less for the entire path of more than 6,000 feet than would be encountered in 100 feet of air at normal pressure. Two beams of light were then sent in opposite directions in the pipe over the circuit ADEF, reflected around the corners by mirrors, and reunited so as to produce interference fringes at A. As a mark from which to measure the displacement a second set of fringes were formed by reflecting light beams around the shorter course, ABCD. Now it will be evident that if the apparatus were stationary in the ether which conveys the light, the two beams would come together without producing an interference fringe since they would then travel equal paths in the same

[5] *The Astrophysical Journal*, vol. 61 (1925), pp. 137-145.

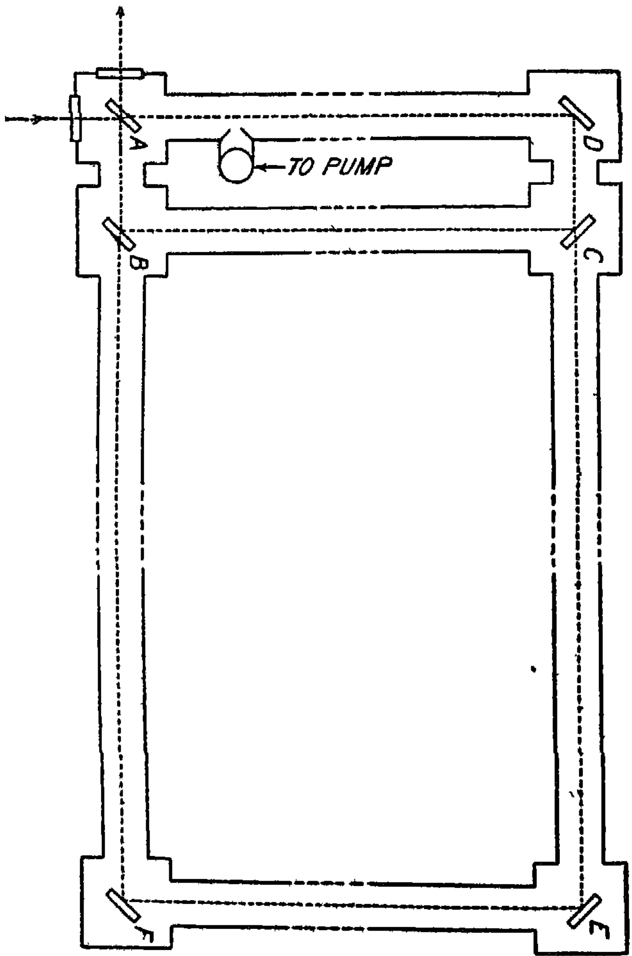

Figure 11.
From the Astrophysical Journal

length of time. If, on the other hand, the line of pipe had a motion through the ether, the case would be altered. It turns out that by any theory the orbital motion of the earth would not produce any effect in the interference of the light. The rotation of the earth, however, is a different matter. In one direction the mirrors would be advancing to meet the light while in the other they would be receding from it. If the pipe line had been laid all around the earth this would be more evident, but in the actual experiment the difference in velocities at points of different latitudes was the effect made use of.

There are three possibilities to be examined in this experiment. Some scientists explained the lack of effect in the original Michelson experiment by assuming that the ether which conveyed the light was dragged along by the walls of the laboratory. As I understand Professor Miller's recent experiment this is one of the conclusions that he wishes us to reach since he obtained comparatively large interference fringes at the top of Mount Wilson and very slight effects in his laboratory at Cleveland, which would indicate a partial drag. This is called the "ether-drag" theory and I shall so refer to it. On this assumption the ether in the heavy pipes at the altitude of Chicago should be carried along by the apparatus and no interference would then be detected.

A different result, however, would be expected on the basis of the "ether-wind' or "ether drift" theory, which assumes that the ether is extremely tenuous and forms a huge, stagnant ocean through which the earth and all material objects move without disturbance.

We see that on this hypothesis the ether moves through matter much as the air would pass through the meshes of a screen carried on a swiftly moving car. It is easily proved that the shift on this basis would be .236 of a fringe or 1/200,000 of an inch, an amount well within the experimental range of the interferometer.

Curiously enough the theory of relativity, which asserts that accelerations, but not velocities, are detectable by interference fringes, leads to exactly the same predicted shift as that obtained by the ether-drift theory. These calculations are made, of course,

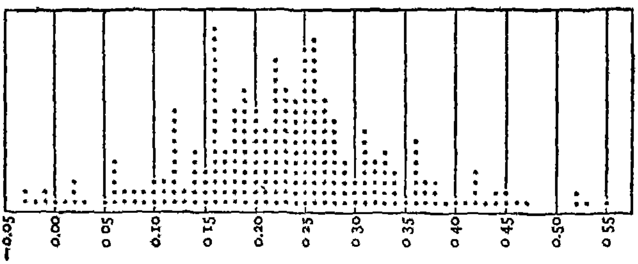

Figure 12.
From the Astrophysical Journal.

on the basis of a space-time element ds, computed for the neighborhood of the rotating earth. A detailed analysis of the considerations which enter will be found in *The Theory of Relativity*, Second edition, (1924) by L. Silberstein, p. 376 et seq. We have, therefore no way of distinguishing between the ether-drift and the relativity theory on the basis of this experiment although the fundamental hypotheses are very different since the one assumes that the shift measures a velocity, while the second assumes that it results from an

acceleration due to the rotation of the earth.

The picture, (Fig. 12) shows the results of the experiment which give .230 for the mean value of the shift, the difference between this and the predicted value being well within the error of the instrument. This experiment, I feel, is a very serious challenge to the ether-drag conclusion arrived at by Professor Miller and must cast doubt upon his conclusions until there is some way of reconciling the two experiments.

I shall next discuss in turn the three deductions from Einstein's theory of relativity which so surprised the world of science when they were announced and which have subsequently received such notable verification.

The first of these is an explanation of a fact long known, but never adequately explained. Mercury, the small planet near the sun, has a peculiar advance in the perihelion of its orbit that can not be accounted for on the basis of Newton's theory of gravitation except by the assumption of the existence of a large quantity of matter in the neighborhood of the sun. This undiscovered matter has been long sought for, but never found. I can not go into the details of the intricate discussion aroused by this point, but it is sufficient to remark that the discrepancy between observation and theory is beautifully and exactly accounted for by the theory of relativity. For Mercury there is an advance of 43″ per century and the difference between the relativity calculations and observations is .58″ with a probable error of .29″. Professor Eddington in his *Theory of Relativity* (p. 90) makes the following remark: "Einstein's correction to the perihelion of

Mercury has removed the principal discordance in the table, which on the Newtonian theory was nearly 30 times the probable error. Of the 15 residuals 8 exceed the probable error, and 3 exceed twice the probable error—as nearly as possible the proper proportion.

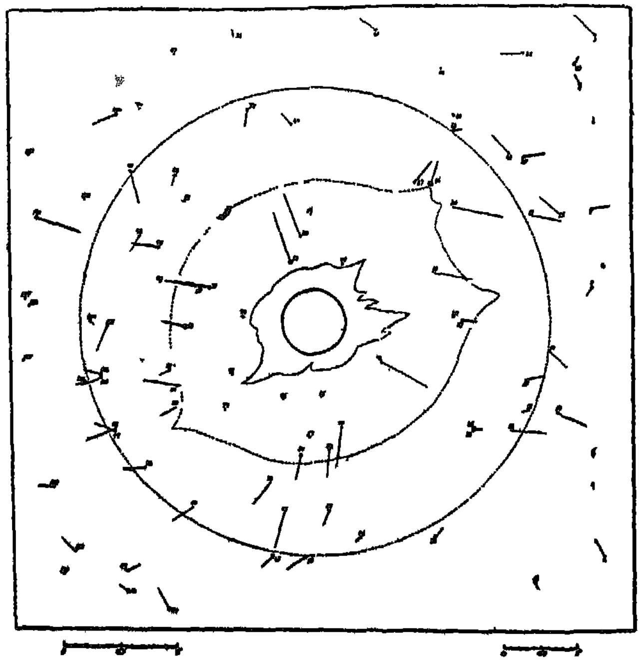

Figure 13.
From Lick Observatory Bulletin, No. 346

But whereas we should expect the greatest residual to be about 3 times the probable error, the residual of the node of Venus is rather excessive at 4½ times the probable error, and may, perhaps, be a genuine dis-

cordance. Einstein's theory throws no light on the cause of this discordance"

One of the most spectacular predictions made by Professor Einstein was that of the bending of light in the neighborhood of the sun The only way in which this could be tested was by making observations at the time of the eclipse and comparing the observed and cal-

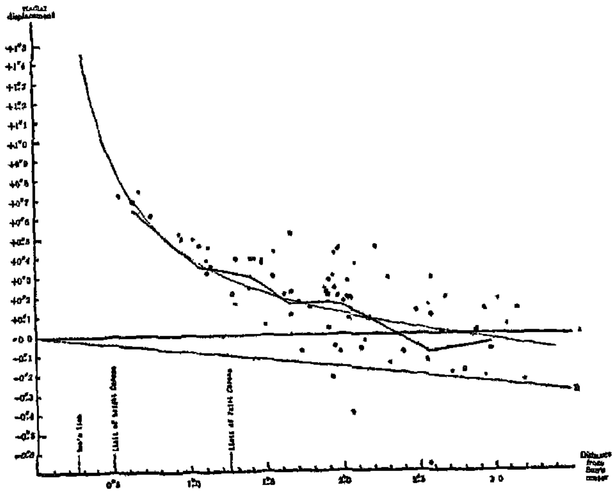

Figure 14
From Lick Observatory Bulletin, No. 346

culated positions of the stars. According to Einstein, light that just grazed the limb of the sun should be deflected 1 75", which is twice that predicted by Newtonian theory. The accompanying photographs show the results obtained by the Crocker Eclipse Expedition to Wallal, Western Australia, 1922. You will observe in the first picture, (Fig. 13), that the stars near

the sun's limb are deflected further than those at a greater distance and it may be calculated that the mean deflection is the value predicted by Einstein within the limits of experimental error. In the second picture, (Fig. 14), the dotted line is the theoretical displacement and the broken line connects the group means of the observed displacement.

The third prediction, which had to do with the displacement of spectrum lines in heavy stars, was for a long time in doubt and Einstein maintained that the validity of his entire theory of gravitation depended upon the truth or falsity of this third crucial test. I must first explain to you that the velocity with which distant stars are moving toward or receding from us can be measured by the displacement of lines in the spectrum. This is known as the Doppler effect and is analogous to the change in pitch of a locomotive whistle as the train is moving toward or away from us. Now according to Einstein's theory, in the neighborhood of heavy bodies a Doppler effect should be observed as a result of the difference between earth and sun time which arises from the change in the four dimensional space-time continuum of the two bodies. On the sun, due to its great mass, time moves somewhat more slowly than on the earth. Hence an atom on the sun would vibrate more slowly than an atom on the earth and this would appear to us as a Doppler shift toward the red end of the spectrum. For the sun this effect is very small, amounting for a wave length of 4000 Angstrom units (10^{-10} m.) to a relative displacement of only .008 of a unit, which is approximately 32 trillionths of an inch. This we could in-

terpret as a recessional velocity of .63 kilometers per second except that we know that no such velocity exists. For a long time observations using the utmost power of available instruments were made in order to detect this shift, but the effect was so close to the limits of observation that little confidence was felt one way or the other.

However, C. E. St. John after a long study of the problem finally concluded in a paper published in 1923 that such an effect does exist on the sun. The following table shows the agreement between the calculated and observed wave lengths for various groups of lines studied:

Group	No of Lines	Mean Wave Length	Calculated Shift	Observed Shift
a	17	3826	.008	.012
b	24	3821	.008	.0112
b	10	4308	.0091	.0113
a	10	5419	.0115	.0112
b	95	4166	.0088	.0072
b	36	6294	.0133	.0115
d	106	4763	.0100	.0069
a	33	4957	.0105	0074

"The conclusion is," says St. John,[6] "that three major causes are producing the differences between solar and terrestrial wave-lengths, and that it is possible to disentangle their effects. The causes appear to be the slowing up of the atomic clock in the sun to an amount predicted by the theory of generalized rela-

[6]On Gravitational Displacement of Solar Lines, Monthly Notices of Royal Astro Society, vol. 84, (1923), pp. 93-96. See also *Proceedings of National Academy of Science*, vol. 12 (1926), pp. 65-68.

tivity, radial velocities of moderate cosmic magnitude and in probable directions, and differential scattering in the longer paths traversed through the solar atmosphere by light coming from the limb of the sun."

Because of the exceedingly small shift in the sun's spectrum, astronomers turned to the sky to find some other object which might serve the purpose better in verifying or discrediting the prediction. Very fortunately such an object exists in the double star formed by Sirius, the dog star, and the small sun that accompanies it. This companion, the White Dwarf as it is sometimes called, is one of the most remarkable objects in the heavens since, although only one ten-thousandth as bright as Sirius, it has about 2/5th of its mass and is tremendously dense, this density reaching the amazing figure of 50,000 times that of water. This figure is all the more fantastic when we remember that the earth is only 5.5 times as dense as water.

Because some people have difficulty in believing that an object as dense as this really exists, it is both interesting and important to review the arguments by which one arrives at such an astounding conclusion.[7]

In the first place we know from observation that the period of rotation of the visible star is 49.3 years and that the major axis of the path of the companion is 20 earth-radii. From Kepler's third law we may deduce without difficulty the following formula:

$$M / M' = \left(\frac{A}{A'}\right)^3 \left(\frac{T'}{T}\right)^2 ,$$

where M is the mass of the double star, T the period of one of the components, and A the major axis of its

[7] See Eddington, Monthly Notices, vol. 84 (1924), p. 308.

orbit; M' the mass of the sun and earth, T' the period of the earth, and A' the major axis of the earth's orbit. Upon substituting the known values in this formula, we find that the mass of the double star is approximately 3.5 times that of the sun. But we can measure not only the path of the companion but also the path of both stars relative to the center of gravity of the system. This leads to the conclusion that Sirius has a mass $2\frac{1}{2}$ times that of the sun and that the mass of the dwarf, consequently, is equal to that of the sun.

In the face of this conclusion a surprising thing is now observed. At a distance of nine light years away the white dwarf is a star of only 8.5 magnitude, which, in less technical language, means that it appears to be only 1/376th as bright as our sun. This, of course, is not so surprising until we learn from a study of the dwarf's spectrum that it is considerably hotter than our sun, having, as a matter of fact, a surface temperature of about 8,000° as compared with 5,900° for our sun. The Stefan-Boltzmann law of radiation states that the total radiation of energy per unit volume is proportional to the fourth power of the absolute temperature of the radiating body. Hence the surface brightness of the dwarf must be actually $(80/59)^4 = 3.34$ times that of the sun.

The facts, then, appear to be these: that the dwarf, while having the same mass as the sun and a surface brightness three and a third times as great appears to be a star only 1/376th as bright as our sun. The obvious conclusion that we can draw from these figures is that the dwarf has a surface only 1/1256 as large as that of the sun and hence must have a radius only

.028 as large as the radius of the sun. This leads immediately to the conclusion that the density of the dwarf must reach the enormous figure of 50,000 times that of water as has already been stated.

Now in the neighborhood of a star of this great density, space and time would be quite different from the space and time in the neighborhood of a body like our sun or like Sirius, so a large Einstein shift toward the red end of the spectrum was to be expected. As a matter of fact the shift as predicted would be as great as .3 of an Angstrom unit as compared with .008 for the sun and this is well within the limits of our instruments.

You will now recall that such a shift can be interpreted in two ways: first, as an Einstein shift, or second, as a recessional velocity in space. In order to show that it is a true Einstein shift, photographs were taken under great technical difficulties at Mount Wilson of both Sirius and the companion at a time when they were moving with a velocity of 1.7 kilometers with respect to one another. Upon comparing the faint lines of the spectrum of the dwarf with the nearly eclipsing spectrum of Sirius a shift was observed slightly larger even than the one calculated by Professor Eddington. If the shift is not an Einstein shift then one alternative explanation is that the companion is moving away from Sirius with a velocity of more than 20 kilometers per second which we know is not the case.

In commenting upon these results[8] W. S. Adams,

[8]Relativity of Displacement of the Spectral Lines in the Companion of Sirius. *Proceedings National Academy of Science*, vol. 11 (1925), pp. 382-387.

who was responsible for the details of the experiment, makes the following remarks:

"Although such a degree of agreement [between predicted and observed values] can only be regarded as accidental for observations as difficult as these, the inherent accord of the measurements made by different methods, and in particular with the registering microphotometer, is thoroughly satisfactory. The results may be considered, therefore, as affording direct evidence from stellar spectra for the validity of the third test of the theory of general relativity, and for the remarkable densities predicted by Eddington for the dwarf stars of early type of spectrum".

Attempts have been made to explain this shift by other means, one explanation being that it is due to pressure, but the spectrum lines used in the experiment are those which are known to be unaffected by pressure. Thus we see that this prediction of Einstein, which for a long time was regarded by relativists as the greatest source of danger to the theory, has proved in the end to give a verification as complete as can be expected under present methods of experimentation.

There are various other experiments supporting the relativity theory which I can only mention in passing. Trouton and Noble sought to determine a motion of the earth through the ether from an expected torque exerted on a suspended electrical condenser by the ether wind. No such effect was found. This experiment has recently been repeated by R. Tomaschek[9] on the Jungfrau in the Alps at an altitude of 11,342 feet (3457 meters) again with negative results. The

[9] *Annalen der Physik*, vol. 78 (1925), pp. 743-756.

bearing of this experiment upon the results obtained by D. C. Miller in his recent drift experiments upon Mount Wilson will be referred to later.

Lord Rayleigh[10] and later D. B. Bruce[11] with a more sensitive apparatus sought in vain for a change in orientation of the optical axis in a body when the axis was changed from a position horizontal to the direction of the earth to a direction perpendicular to it. This was a conclusion consistent with relativity since the discovery of such a change would have led to the discovery of an absolute velocity in the ether.

The fine structure of spectrum lines is beautifully accounted for by Professor Sommerfeld as an effect due to relativity.[12] We believe now that the phenomenon of the occurrence of lines in light spectra is caused by the motion of the electrons in the matter which is emitting the light. We also believe that the electrons are all moving in their orbits within the atoms with high velocities, so that the relativity effect upon their motions should be very much greater than that found in the motions of bodies like the earth and the planets where the velocities are comparatively low.

Suppose, then, that one of these electrons is moving in an elliptical orbit about its sun, the so-called nucleus or proton of the atom. The relativity effect would then exhibit itself in an advance in the perihelion of the orbit of the electron. In other words the diameter of the ellipse would move forward with every revolution of the electron and its two extremities

[10] *Philosophical Magazine,* 6th ser., vol. 4 (1902). p. 678.
[11] *Philosophical Magazine,* 6th ser., vol. 7 (1904), p. 317.
[12] *Atomic Structure.* English Translation (1923), Chapter 8.

would trace out the arcs of concentric circles as illustrated in figure 15.

Using the hypothesis of the quantum theory which says that the energy radiated or absorbed by an atom is determined by abrupt jumps of the electrons from one possible orbit to another, we find that the relativity effect actually appears in a measurable way in the formulas which determine the spectrum lines of the radiation. This effect exhibits itself as a fine division of spectral lines which, without taking account of the

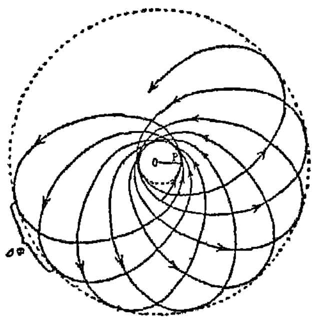

Figure 15.
From A. Sommerfeld in Atombau und Spektrallinien.

relativity hypothesis, should have appeared as single lines. This *fine structure* in the Hydrogen spectrum has been completely verified by experiment and, according to Sommerfeld, gives "ocular evidence not only of the actual occurrence of the elliptic orbits, but also of the variability of the electronic mass."

The subject of the aberration of light has already been mentioned, but since the phenomena connected with this theory are exactly and simply accounted for by the principles of relativity I shall take a few mo-

ments to present the argument. My colleague has already mentioned that the addition of velocities follows a new law. We no longer can say with Newton that a man who is walking three miles an hour down the aisle of a railroad coach moving at the rate of 30 miles an hour is moving with a velocity of 30+3 miles an hour with respect to the earth. We must say with Einstein that he is moving with the velocity of

$$\frac{30+3}{1+30\times 3/c^2}$$

where c is the velocity of light. In other words velocities are compounded according to the formula

$$u'=(u+U)/(1+u\,U/c^2).$$

The entire theory of aberration follows from this simple consequence of the theory of relativity.

Thus our opponents have explained to you that when a beam of light is sent through a moving column of water the phenomenon of an ether-drag is exhibited and the coefficient of this drag is $1-1/\mu^2$ where μ is the index of refraction of the water. Let us suppose that v is the velocity of light in still water, which we know is connected with the index of refraction by the formula $v=c/\mu$, where c is the speed of light. If, then, the stream of water moves with the velocity u, we shall obtain as the total velocity of the light the value $(v+u)/(1+v\,u/c^2)$ which reduces to $v+u(1-1/\mu^2)$ by neglecting terms containing the reciprocal of the velocity of light. This result is consistent with the classical theory and, as you can see, is obtained in the simplest manner and without the necessity of making any assumption whatever about the structure of matter.

Astronomical aberration is just as easily explained on the basis of the relativistic addition of velocities, but since the mathematical details are somewhat involved the derivation of the formula will be omitted. It is interesting to observe, however, that the classical theory and the relativity theory lead to formulas which differ in terms of second order so that it may be possible some day to distinguish between them when more refined instruments are available.

One of the most interesting phenomena in the theory is the gain of mass experienced by a body when in motion, a gain which is exactly accounted for by the theory of relativity. Experiments showing this difference in mass for various velocities were carried out by A. H. Bucherer in 1909. Our opponents wish to reinterpret these results as indicating a change in the charge rather than a change in the mass of particles studied. However, upon this point we are all in agreement, that something changes with velocity and since a change in mass of the desired order is predicted from the postulates of relativity, the experiment, far from leading to a contradiction with the theory, must increase our confidence in it.

I turn finally to a consideration of the remarkable experiments of Professor Miller. I do not expect to explain them, nor can I feel, after considering the careful technique employed, that there is a large experimental error in them. Some kind of a disturbance was found in the ether at the top of Mount Wilson that was not found at Cleveland. What I do take exception to is the explanation that this disturbance is due to an absolute velocity in space since such a conclusion is in

contradiction with the principles of relativity. In support of this contention I shall first show that the results of Professor Miller are not in agreement with the proper motion of the earth as it has been calculated from a study of the proper motions of the fixed stars.

Apex der Sonnenbewegung

$\alpha = 270^0$ $\delta = +32^0$ $v = 20$ km/sec

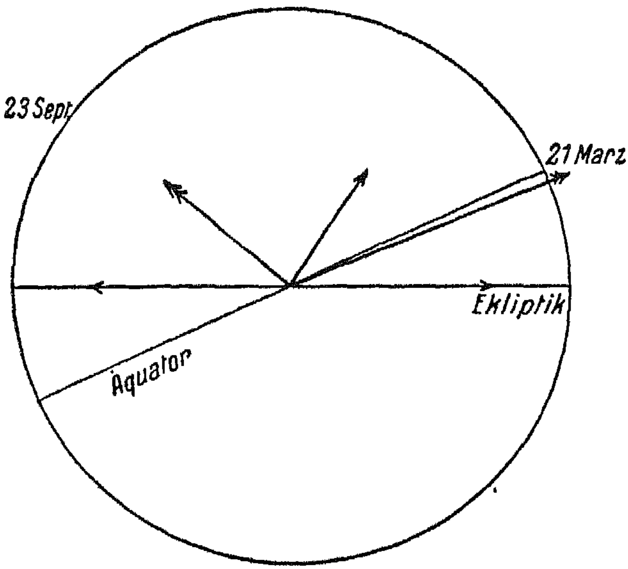

Figure 16
From J. Weber, Physikalische Zeitschrift.

As you are aware the earth turns on its axis once a day and moves around the sun with an average orbital velocity of 18.6 (30 km.) miles per second. In addition to this the earth shares a motion with the sun in space which has been estimated to be about 12 miles

(20 km.) per second in the direction of the constellation Hercules. (R. A. 270°, δ=32°). You will see in the diagram of figure 16[13] three vectors with single arrows which represent the velocities of the earth as

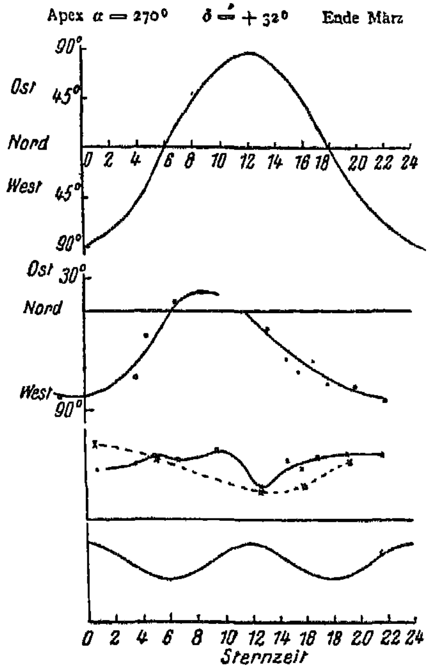

Figure 17.

we know it from a study of the framework of the fixed stars. The arrows in the ecliptic represent the orbital velocity of the earth on March 21 and September 23 respectively and the arrow 32° above the equator shows

[13]From J Weber: *Physikalische Zeitschrift,* vol. 27 (1926) p 5.

the direction of the velocity of the entire system. If these two velocities are compounded into a single velocity represented by the double headed arrows, we find that the velocity of our earth on March 21 is very close to the plane of the equator and on September 23 is about 65° above the equator. In simple language this means that the interferometer should show a difference in the magnitude of the earth's velocity at different times during the year, a thing Professor Miller did not find since nearly identical readings were obtained both in September and March. You will see from Figure 17 (Weber) the discordance between Miller's results and the calculated curves both in direction and magnitude. If the earth is moving through the ether in the direction that we have many reasons to think it has, then the apparent direction of the velocity at Mount Wilson should change for every hour during the day in a regular sinusoidal curve. You will notice that the azimuth angle in Professor Miller's curve is zero at 12 o'clock when as a matter of fact it should have its maximum value at that time.

In order to meet the difficulty that his observations do not show a variation with the time of year, Professor Miller then assumes that we are really moving in a direction quite different from what we think we are by referring to the framework of the stars and with a velocity that is much greater. As a matter of fact he believes that the velocity of the solar system is not 20 km. per second in the direction of the constellation of Hercules, but is probably more than ten times as great in the direction of the constellation Draco (R. A. 262°, $\delta = +65°$). In order to support this assumption Pro-

fessor Miller then points out that a velocity of approximately this direction and magnitude is obtained from a study of the proper motions of the globular clusters. I should like to point out, however, that if we are bold enough to refer our coordinate system to the spiral nebulae we might arrive at the conclusion that we are *moving* through space with the incredible velocity of perhaps 1,000 km. per second. It is this very fact that there are no "natural axes" in the heavens to which we can refer our "absolute velocity" except the intangible wraith of the "fixed ether" that, in my opinion, gives relativity one of its most powerful arguments. I do not contend that Professor Miller may not be able to assign a direction and a magnitude to the velocity of the earth in space which will be mathematically consistent with his experimental results, but that to talk of such an "absolute velocity" as having any relation to the matter of the universe is without meaning.

A second argument seems to show that Professor Miller has not written finis to the theory of relativity. This is the contradictory results obtained by Tomaschek in his repetition of the Trouton and Noble experiment on the Jungfrau to which reference has already been made. In Miller's paper on the "Ether-drift Experiments at Mount Wilson" published in 1925 he makes the statement: "The ether-drift experiments at Mount Wilson during the last four years, 1921 to 1925, lead to the conclusion that there is a relative motion of the earth and the ether at this observatory of approximately nine kilometers per second, being about one-third the orbital velocity of the earth. By comparison with the earlier Cleveland observations, this

suggests a partial drag of the ether by the earth, which decreases with altitude". Professor Miller in his report in *Science* in 1926, however, makes the following statement which is apparently in contradiction with the conclusions previously obtained: "The evidence now indicates that the drift at Mount Wilson does not differ greatly in magnitude from that at Cleveland and that at sea-level it would probably have the same value". If the latter statement is to be accepted as the final conclusion, then it appears that the Michelson-Gale experiment is still in contradiction with the Mount Wilson results, if, on the other hand, the ether-drift is affected by altitude, then the results of Tomaschek are also in contradiction. Tomaschek makes the following statement on this point: "In case the positive result of the Michelson interference experiment is confirmed, the result obtained in this work [The Trouton-Noble experiment] will mean an entirely new and up to now wholly unexpected behavior of the electro-magnetic field connected with matter, of the lines of force connected on the one hand with the charge and on the other hand of the field found in light rays." It appears, therefore, that we have a conflict of experimental evidence and until all of the experiments have been repeated under identical conditions, it seems that the part of wisdom is to withhold final judgment.

A third argument that seems cogent to me is that the actual optical properties of the rotating framework of the earth have not yet been thoroughly investigated as has already been indicated. The acceleration field obtained by compounding the orbital velocity of the earth with its rotation can not be neglected entirely

and if to this is added the gravitational field of the earth, the coefficients of Einstein's fundamental line element,

$$ds^2 = \sum_{ij=1}^{4} g_{ij}\, dx_i\, dx_j\,,$$

might be found to differ substantially from those in free space. Until a further investigation of optical phenomena on the earth is made on the basis of this corrected line element, the results of the Miller experiment can not be said to be in contradiction with the theory of relativity. There are certain small anomalies still existing in the theory of aberration which makes that subject one of perennial interest to the astronomer although nearly 200 years have elapsed since it was discovered by Bradley. Miller has suggested that these might be an indication of a variation in the ether at different stations on the earth. Until we know more about the proper motion of the solar system there is no reason why we could not explain such variations as being indications of a hitherto undetected acceleration of the system.

In conclusion let me state that the succession of steps by means of which we have arrived at the theory of relativity tends to increase one's belief in the validity of the fundamental postulates. The Maxwell field equations of electromagnetism are direct mathematical consequences of the experimental work of Faraday and Ampere and rest upon the secure foundation of successful explanation of known phenomena and the prediction of new. The remarkable fact that these

equations are invariant under the Lorentz transformation is enough, it seems to me, to have led to the restricted theory of relativity even without the experiment of Michelson and Morley. This fact, seldom sufficiently emphasized, seems to me to be one of great significance since it came out of the equations long after their formulation and could not have been put there by design. The only other fact that seems to me to compare with it in the history of physical science is the identification by experiment of the physical constant which appears in the same equations, with the speed of light.

THE FOURTH DOCTRINE OF SCIENCE AND ITS LIMITATIONS

The Rebuttal of the Negative by Professor MacMillan

During the past one hundred years there have arisen four great doctrines in the scientific world. Curiously enough two of these doctrines have met with universal approval among scientific men, while the other two have met with a violent disapproval.

The first of these great doctrines is the doctrine of the conservation of energy. Without attempting to define what energy is, merely recognizing it as the source of the activities of nature, it is asserted that energy can be neither created nor destroyed. It changes its form from potential energy to kinetic energy and back again, and these changes are the activities of nature, but its total amount is neither increased nor decreased. That something should remain constant in the world of increasing change and flux has an almost universal appeal to our esthetic sense, and the doctrine of the conservation of energy commands an almost universal approval.

The second of these doctrines which enjoys the hearty assent of the scientifically minded is the doctrine of evolution. I do not mean evolution in the narrower sense of biological development, but evolution in the broader sense of the continuity of the physical universe throughout all time, and the orderliness of the processes of change which go on unceasingly. Every physi-

cal unit which we recognize in nature, electrons, atoms, crystals, cells, stars, galaxies, has at some time come into existence and at some time in the future will pass out of existence; and furthermore the manner of their coming and going is quite orderly, and, within reasonable limits, is even predictable. No physical unit is permanent in the sense that it always has existed and that it will continue to exist throughout all time. Our sense of permanency is quite satisfied with the doctrine that energy is constant, and our sense of change also is satisfied with the doctrine that no physical form endures forever. Like the individuals of the human race, all of the physical units of nature come and go in unending sequence. The manner in which they come and go is the subject matter of science, and the intense scientific activity of the present time is a real measure of our intellectual curiosity. Our willingness to grant these two fundamental postulates merely expresses our readiness to believe that science is possible, and that the activities of nature are not merely capricious.

In contrast with these two postulates which have been so favorably received are two other great doctrines which have aroused a vast amount of disapproval. The first of these is commonly called the second law of thermodynamics. It implies that the physical universe is a mechanism which, like a clock, is running down. The energy of the universe, notwithstanding it is constant in amount, is always degenerating into heat and being radiated away, and is no longer available for useful work. . Hence if the universe is to continue indefinitely in its present form, like the clock it must at some time in the future be wound

up by some outside agency. If this does not occur either the universe passes into a state of complete stagnation or into some other state in which the physical units with which we are acquainted no longer exist.

Notwithstanding that such a doctrine is repellent to our philosophical instincts, it is a doctrine which is expressible in mathematical form and which can be used in predicting physical and chemical phenomena. Even though our esthetic feelings are outraged, it has a thoroughly reputable standing among scientists, for in all of their operations they find that the doctrine is verified. We can not help but wonder why the universe has not run down long ago, and such a thought certainly makes us withhold our assent, however useful the proposition may be in our laboratories. Just as the universe far transcends our laboratories, so also must the postulates of our philosophies transcend our experience. We withhold our assent to this doctrine, not because it is out of harmony with our experience, for quite the contrary is the case, but because it violates our esthetic sensibilities.

I have myself had the pleasure of suggesting an escape from its philosophical implications while still admitting its validity in the laboratory.. The physicists have made us acquainted in recent years with the fact that the atoms are built up of electrons which are of two types, the positive and negative units of electricity. In ordinary matter these two kinds of electrons are numerically equal and therefore ordinary matter is electrically neutral at ordinary distances. The property of mass, however, depends upon the existence of electrical fields of electrons. As long as the electrons are

separated, as they actually are in the atom, the electrical fields exist and the atom possesses the property of mass. If the organization of the atom is destroyed and the electron and proton fall together and actually unite, an enormous amount of energy is liberated, and the two electrical fields, exactly superimposed, no longer possess the property of mass. The resulting physical unit does not have the properties of ordinary matter. From an astronomical point of view this hypothesis has great merit, for it is the only adequate hypothesis which we have to account for the vast amount of energy which the sun and the stars have radiated into space over the enormous periods of time which have elapsed since they came into being.

If the atoms are destroyed and consumed in the fiery interiors of the stars, they are re-formed by the radiant energy in the quietudes of astronomical space and it is in this manner that the gaseous nebulae of the skies come into existence. It is for this reason, too, that the night skies are cold and black, for the energy has been absorbed in the manufacture of atoms. I have not the time now to go into details, but this hypothesis is very effective in harmonizing our knowledge of things celestial. It is also very effective in harmonizing the second law of thermodynamics with a normal system of philosophical postulates.

The second law of thermodynamics is of the same type as the statement: "Water always flows down hill". Everyone will grant that statement. It is true, but it is not the whole truth. Water in the *liquid* form will flow down hill, but in the form of vapor it is equally natural for water to rise. One would naturally expect

some similar statement to apply to energy when it is locked up in atomic form and the atom is tossed about by the various forces which it encounters on its way from its birth place in the depths of astronomical space to the place of its extinction in the interior of some star. But like the water when in the state of vapor the law is reversed when the energy is in the radiant form, and therefore in the long run there is neither up nor down. The average is neither way, merely "continued existence."

The second great doctrine which has encountered disapproval is Einstein's doctrine of relativity. This doctrine belongs essentially to the domain of geometry. It neither adds to nor subtracts from our stock of physical knowledge. It seeks a re-interpretation of our experience in the light of a certain type of non-Euclidian geometry. To one who is not prejudiced against it, but who seeks merely to see what it can do, it seems to have had some success in interpreting certain measurements which the discussions of Professor Hufford and Davis have very ably brought before you. A relativity enthusiast will assure you that his interpretation is completely successful. A neutral thinker, however, is more cautious. In none of the critical experiments can the success be said to be complete. At best the success is but partial. You are satisfied, I think, that the experiments are all very difficult and that it is not possible for us to say with any precision that is satisfactory just what the facts are. The individual observations are singularly discordant and the discrepancies are too great to make the averages of the observations highly trustworthy.

Perhaps the most successful prediction is that relating to the perihelion of Mercury. But even here one remembers that the astronomical values given by Leverrier and Newcomb depend upon certain discordant residues which remain after a very long and arduous process of mathematical distillation. These residues are discordant, probably, because it is impossible to make observations which are perfect, and so all the imperfections in the observations of a hundred years, both of a systematic and of an accidental character, appear in these residues. They could not be made to harmonize perfectly by any process whatever except by the elimination of all of the errors of observation, and that is out of the question. Time, and improved observations, alone can tell whether the figures given by Leverrier and Newcomb represent anything real; and that quite likely will be a matter of many decades, even if not a matter of centuries. As the matter stands at present, however, the agreement between the figures of Newcomb and Einstein is astonishingly good.

As for the results of the bending of light rays from stars appearing near the limb of the sun during an eclipse of the sun by the moon, I believe Professor Campbell of the Lick Observatory has stated that the results of the observations agree so well with the predictions of relativity that the Lick Observatory will make no further observations along this line. It is impossible for me to share with Professor Campbell in this positive conclusion. The agreement to which he refers is statistical only. The diagrams which show the predicted displacements and the observed displacements are certainly not very similar. Not only do the radial

displacements differ, when considered individually, but there are relatively large tangential displacements which Einstein does not predict at all. The number of stars considered was less than one hundred, and such a small number does not give a statistical conclusion great weight; and particularly is this true when the predicted displacements and the observed displacements are, individually, widely discordant.

It is well known that the predicted shift in the lines of the spectrum of the sun could not, at first, be found. The best equipment for such observation is undoubtedly in the solar observatory at Mount Wilson, and no observer is more careful and trustworthy than St. John. For several years he was skeptical about the predicted shifts. Like all the other critical tests the matter is very difficult, not because the shift itself lies beyond the reach of measurements, but because the lines of the sun are shifted from other causes. Eventually, however, a system of corrections was found which brought the observations and the theory into accord, and the matter was so announced by St. John. The agreement between theory and observation was not a simple one, as in the previous cases. Certain corrections must be applied. The skeptic is rude enough to suggest that perhaps there are yet other corrections which should be applied, and that one can never be sure that the list is complete. These possibilities do not disturb one who wants to believe, but they are certain to occur to one who does not.

The dwarf-white companion of Sirius has attracted much attention of late because it is alleged to be fifty thousand times as dense as water, or twenty-five hun-

dred times as dense as platinum—approximately one ton per cubic inch. For such a star the theoretical shift of the lines of the spectrum is very large. Unfortunately the star is so close to the very brilliant Sirius that it is hard to get a satisfactory spectrum. Nevertheless Adams thinks the predicted shift is observable, although he seems to admit some uncertainty.

It would require a great deal of evidence of a very high character to convince a normal man that a whole star is twenty-five hundred times as dense as the densest terrestrial substance. The difficulty is much the same as would be encountered in expecting a lover of athletic sports to believe that a new athlete had appeared who could jump fifteen thousand feet high, or one who had extended the record for the running broad jump from twenty-five feet to twelve miles. Human credulity does not often take such flights, and we must admire the strong nerves of the man who puts forth such startling ideas seriously. He must not expect us to take it seriously, however, and we can only smile when he asks us to regard such statements as evidence of anything whatever. Doubtless there is something peculiar about the companion of Sirius, but the evidence is far too feeble to support the extraordinary conclusion which has been placed upon it.

I come finally to the experiments of Professor Dayton C. Miller, which are repetitions of the original Michelson-Morley experiments of a more refined character and under a greater variety of conditions. There seems to be little disposition on the part of anyone to doubt that Professor Miller has actually measured something. The doubts all rest on the interpretations

of what he has measured. The relativist, who is committed to the idea that there is nothing to measure, is puzzled and is looking around for something he had not thought of before. He wishes to keep his postulates, and yet find an explanation for the new experience. That it can be done I have but little doubt, for I do not think that the differences between the relativists and the classicists can be decided permanently by experiment. Miller's experiment is at least a temporary check to the triumphant march of relativity. That such a check would be encountered sooner or later was to have been anticipated, for no formula will ever prove to be a universal solvent of physical difficulties.

The differences between the relativists and the classicists lie beyond the reach of experiment. They are of the same character as the differences between the Presbyterians and the Baptists. They are postulational only, but inasmuch as the relativists have deliberately abandoned the intuitions, which are, so to speak, the eyes of the intellect, it is impossible to believe that any large portion of the human race will follow them into their difficult and dark domain. Most of us will prefer the open sunshine of our intuiion, which undoubtedly is one of the most treasured inheritances of our race.

Let me conclude my argument by summarizing briefly the situation as it appears to me. The object of science is to build up an intellectual system in which the well verified experiences of the human race are coordinated and unified and from which suggestions are derived for the extension of that experience. This intellectual system is a structure which rests upon a

relatively large number of concepts which cannot be defined, but which serve as a basis for the definition of secondary and other subsidiary concepts, and a large number of postulates which cannot be proved, but which serve as a basis for the establishment or proof of other relations which are logically derivable from them or of hypotheses which make a direct appeal to experience. These undefined concepts and unproved postulates are suggested to us by our experiences with the world about us, but there is nothing absolute or necessary about them.

Quite likely infinitely many sets of concepts and postulates are adequate for the interpretation of such experiences as the race will have, and no one set, in itself, can claim priority. Nevertheless, owing to the particular experiences which the race has had and the order in which these experiences have occurred, our intuitions have been developed in such a way that the geometry of Euclid and the mechanics of Newton seem to be their natural expressions, and non-Euclidean geometries and non-Newtonian mechanics, while logically coherent, are essentially unintelligible until their propositions can be interpreted in terms of Euclid and Newton. The mechanics of Einstein are non-Newtonian in character and make no appeal to our intuitions. Consequently our intellects, being what they are, will not be satisfied with an explanation which is incomprehensible. They will always cry "Speak to us in a language which we can understand. We are not satisfied with mere formulas."

For the sake of a very few minute and obscure phenomena the relativists ask us to change the very struc-

ture of our mental being. Even worse, some of them are bold enough to assert that we must change, thereby implying that their system of postulates occupies a unique position among all possible systems of postulates. There is no assurance as yet that even these minute phenomena satisfy the claims of the relativists. The measurements are very difficult, and the errors of measurement may be several times the magnitude of the quantity which it is sought to measure. Unless there is a perfect agreement between the predictions of relativity and the results of measurement all of the advantage which its adherents claim is lost and relativity will be reduced to its proper place of equality among the postulational systems. And even if the agreement should turn out to be perfect, the advantage will be only of a temporary character. In the long run our geometries and our mechanics will reflect rather the nature of our intellects than the nature of the universe which we are trying to understand.

PHILOSOPHICAL IMPLICATIONS OF THE THEORY

The Final Rejoinder of the Affirmative by Professor Carmichael.

It is inspiring to come before an audience which is still alert after listening for two hours to arguments concerning such minute differences of measurement as those involved in the crucial tests of relativity. Let us note how exceedingly small is the shift in the spectral lines of light coming from the sun. We take that part of the spectrum where the requisite measurements are most easily made. The length of the shift can be realized in the following way. Begin with a stick a meter long. Take one-tenth of it; then take one-tenth of the small piece thus obtained; then take again one-tenth of the piece retained; then again one tenth of this; and continue the process for ten consecutive steps. Having done this, divide the exceedingly small length which remains into 125 equal parts and retain one of these parts. This is the amount of the spectral shift involved.

It is inspiring to witness that divine curiosity of the human intellect which compels a general and profound interest in theories which differ experimentally by such minute quantities as that just indicated. The human mind is not satisfied with a theory which is nearly in agreement with fact. As long as there is the minutest difference which may be detected by measurement there

is a struggle forward to arrive at precision of agreement between theory and observation—not because the small observational difference is a matter of deep concern, but because it is such small differences as these which enable us to choose between rival philosophies of science.

It is inspiring, as I said, to see the ardor of interest on the part of this audience undiminished after two hours of continuous debating, especially when one remembers the fact that we have here not merely physicists and mathematicians, who have a professional interest in the subject, but also chemists and biologists and classicists and business men and, indeed, those whose main interests are of the most diversified character. It is a striking witness to the divine curiosity of the human spirit.

There are three main demands, as we said last night, which the human spirit will insist upon in the case of any scientific theory that is a claimant for acceptance: It must be in suitable agreement with the facts of nature; it must have those esthetic qualities which render it pleasing to the human spirit; and it must furnish what is to us the most agreeable theory from the point of view of convenience. In the light of all that has now been said let us reexamine the theory of relativity with regard to the way in which it meets this fundamental test.

In making this analysis we shall be guided by the implications of the following postulate: "A conception exists for physics only insofar as it is possible to determine whether it is true or not," that is, whether it is consonant with fact. Moreover no basis of physical

science can be considered satisfactory, even as a temporary halting stage, which requires, for its application to phenomena within its range, the frequent introduction of *ad hoc* hypotheses, special hypotheses brought in to make it possible to find a suitable explanation of phenomena in restricted ranges. This is a violation of the principle of convenience in physical theory—a principle whose importance has been insisted upon by Copernicus and by others since his day. The use of *ad hoc* hypotheses is an admission of essential defects in a theory. It should be insisted upon strongly that a fundamental theory should be so based that it is unnecessary to lay temporary or tentative foundations to support important parts of its edifice. The foundation should be sufficient to carry the whole superstructure of that domain of truth for which it is suitable. A theory of gravitation does not need to embrace electromagnetic phenomena, but it is essential that a theory of gravitation should embrace all gravitational phenomena. Otherwise the theory is distinctly defective.

For this reason we must reject as unsatisfactory the explanations of the perihelion advance of Mercury, as accounted for (up to the present) on other bases than that of the theory of relativity. All such explanations, so far as I am aware, depend upon *ad hoc* hypotheses. If it should turn out—when the matter has been thoroughly sifted—that there is a real discrepancy between the theory of relativity and the aberrations in the motion of the planet Venus, then there would be a valid objection to the theory of relativity. For some years I have believed that the whole problem of the

perihelion advance of the planets should be worked out anew both theoretically and by analysis of the records of observations. This remark applies to the motion of Mercury as well as that of the other planets. Until this has been done I do not think that we are justified in trying to pronounce final judgment on the matter. The theoretical basis needs to be examined more rigorously. When this is done the results, as I anticipate them, will be in favor of relativity.

Owing to the same objection to *ad hoc* hypothesis, I think that we should not at present place any great emphasis upon the possibility of explaining the fine structure of the spectrum lines by alternative hypothesis. But in this case the experiment does not furnish a crucial test of relativity and hence is not decisive one way or the other. That there is an explanation on the basis of the Einstein theory is interesting to the relativist but he can hardly consider it a matter on which the theory must stand or fall.

Furthermore these alternative explanations, it appears to me, are often considered in a false light. They are sometimes presented as if the existence of an alternative explanation of a phenomenon is in some sense a blow to relativity. But this is clearly not so, as any one must see who remembers what we said last night, on the basis of a proof by Poincaré, that if there is one explanation of a class of physical phenomena then there is an infinitude of such explanations. Thus from the existence of an explanation by means of relativity, one knows in advance that there will be an infinitude of explanations. Therefore it can not be a blow to relativity to have one of them pointed out.

The question that needs to be asked is this: Among these possible explanations which is the most convenient and agreeable? On the answer to this question turns the decision to be rendered. And the presence of an *ad hoc* hypothesis in one of the explanations is sufficient of itself to damn that one.

We must return once more to the question of simultaneity and we must again reject the notion of absolute simultaneity as a scientific conception for the simple reason that there are no physical means for determining absolute simultaneity. The active past of an event, or its active future, can be determined by physical means—by a method which is obvious from our definition of these conceptions as we gave it last night. From this we have a physical means of determining what is contemporaneous with a given event, as we have defined that term. We saw that there is a certain range within which we must confine whatever is to be called simultaneous with an event, using simultaneity as a conception of physical science. Nothing has been given during the debate to show any more precise way of approach toward a definition of absolute simultaneity. The notion that simultaneity is a relative matter, within the named restrictions. must therefore stand as either unchallenged or at least as not successfully controverted. Perhaps we may then agree that it has been established that there is a certain relativity in the conception of simultaneity as an element involved in physical science.

If this is accepted, then the classical mechanics must go, for it is based upon the conception of simultaneity as something absolute. Since our opponents

have shown us no physical means of determining absolute simultaneity, it seems that even they must acknowledge this overthrow of the classical mechanics.

There is another conception of simultaneity which does not belong to physical science but rather to psychology. It is necessary to say a few words about that because the psychological notion of simultaneity has sometimes been confused with the conception of simultaneity in physical science. Whatever is present to a given mental event constitutes a presented simultaneity. I may feel a pin prick just as I "see" a distant star, so that I can not say that either of these experiences precedes the other. They are together in *the mental event. Psychologically they are simultaneous.* Yet I may conclude, upon analysis, that the light which I see left the star a thousand years before I felt the pin prick, even though the two experiences I have are but parts of one and the same mental event. It is thus apparent that psychological simultaneity is not the same as simultaneity in physical science. A confusion of the two has led to a large part of the difficulty which many people have with the relativistic conception of simultaneity. These two conceptions of simultaneity are both important and both deserve the most careful investigation, but only one of them belongs to the measurable entities of physical science. As long as people supposed that things happen when they are seen the confusion of the two was natural. But the attempt to correlate events as happening when seen had to be given up when it was observed that the successive eclipses of Jupiter's satellites are seen at shorter intervals when Jupiter and the earth

are approaching each other than when they are receding from each other. The confusion of the two notions can now be allowed to stand no longer. Simultaneity in physical science is relative to a system of reference, and on such a system it requires physical definition by means of a technical process.

It is both inconvenient and out of accord with the facts to try to hold to the notion of absolute simultaneity.

If the time permitted, I should like to call to your minds again those esthetic qualities which are suitable to render the theory of relativity pleasing to the human spirit But it would be largely a matter of repetition. You will have an increasing appreciation of the fact involved as you become more and more familiar with the beauty and simplicity and elegance of the fundamental principles of relativity, and you can not appreciate it fully until you reach that familiarity. Consequently I shall pass on at once to examine further the experimental evidence for or against the theory: for, after all, every theory must stand the fundamental test of fact.

The three crucial tests have been so analyzed by my colleague that there is little further to be said about them. It is admitted that there is a certain room for difference of opinion about them; the contrary could not be successfully maintained before you who have heard this debate. We can only say that no difficulties about them have been raised which we had not encountered before; and, having examined them in the light of these difficulties, we are still convinced that the preponderance of the evidence afforded by them is in

favor of the theory of relativity and that there is no rival theory, not vitiated by *ad hoc* hypotheses, which can approach the theory of relativity in its success in accounting for them.

Since it is the Miller experiment, more than any other recent one, which has so given heart to the opponents of the theory of relativity, we must return to that experiment, even at the risk of repeating some of the things which were said a while ago by our colleague. We have no doubt that this experiment is an important one. Too great care was taken with it for us to assume that it involves a crude error. The greatest mistake which we could now make about that experiment would be to treat it as unimportant. Our question turns upon the interpretation to be given to the results.

To begin with let me point out that whatever the results are they can not afford a direct contradiction of the principles of relativity as they have been formulated since the appearance of Einstein's 1916 memoir. If there is an incompatability between the facts and the theory it must be brought out by showing that the facts are out of agreement with some consequences of the principles; it is only in this indirect way that such a discrepancy can arise. I hasten to add that it would be just as fatal to relativity to have it arise in this way as in any other. My insistence is upon the proposition that the discrepancy can be shown to exist only by proving that certain consequences from the principles as a whole are out of agreement with the facts. There is no one principle which these facts directly show to be false. This arises from the limitation

to free space involved in the statement of the restricted principle of relativity, while the experiment itself was performed in the presence of a considerable mass of matter (namely that of the earth) and in a field of acceleration due to the revolution of the earth on its axis and to its motion around the sun.

In order to establish a contradiction between the theory of relativity and the Miller experiment one would have to find out what effect these fields would have on the experiment as determined by the theory of relativity itself. This has never been done, so far as I know; certainly our opponents in this debate have made no claim of having tested the matter in this way. Consequently they have not established a contradiction between the theory of relativity and the Miller experiment. It is still an open question as to whether there is a contradiction or not.

In the past it has usually been said that the Michelson and Morley experiment is properly accounted for by the special theory of relativity. Heretofore it has been assumed that the gravitational field of the earth is sufficiently small to be negligible even in the case of the Michelson and Morley experiment; and it is on the basis of this hypothesis—which seemed to be justified by observation—that the special theory of relativity has been supposed to account for the facts. No one, so far as I know, has examined this experiment to see in how far the results would be modified by the actual gravitational field of the earth, because experiment seemed to indicate that no such analysis was needed. Now that we have the additional information afforded by the Miller experiment—if its results stand the test

of analysis and are corroborated—we may find it necessary to treat the experiment on the basis of the general theory of relativity. This would probably lead, I think, to the conclusion that in the neighborhood of the earth the space-time does not sufficiently approximate that of free space to justify us in treating it as such, at least in the case of the Miller experiment. At any rate I feel sure that this is the first thing for the relativists to test out, as far as I know, the examination has not been made. Until it has been made we can not say with certainty what the relation of the Miller experiment is to the general theory of relativity.

We have not the time to consider the experimental evidence further. Since all the available evidence of this kind has been published there was no chance that our opponents could confront us with facts which were unknown to us. All of them we had examined before and we still remain convinced that none of them requires us to give up or even to modify the theory of relativity. We had thought the matter out before and we still retain our former conclusions and for the same reasons which had formerly seemed sufficient to us.

The beautiful lecture delivered by Professor MacMillan last night must now be subjected to analysis. You can never know beforehand what a brilliant Scotchman will do; and so we could not anticipate the line of argument which we heard last night. To subject that argument to analysis is a difficult task for me, since it is hard to know whether it was he or I who said the most last night in favor of the theory of rela-

tivity. With the general philosophical basis from which he started I am in profound agreement. The only way in which the treatment of natural phenomena can be made satisfactory is to put it frankly and clearly on a postulational basis, and to bring the postulates into the clear light of a precise statement. There are innumerable ways in which these postulates may be set up. They can not be chosen capriciously, and yet they are to a large extent arbitrary. There is no one system which is true while the others all are false. The different suitable systems merely represent different ways in which the postulates may be formulated, and it is possible to have numerous systems each equally true. The primary bases of our choice among suitable systems must ultimately be that of esthetic satisfaction and primarily that of convenience. The demand for convenience turns the scale in favor of that system requiring the fewest *ad hoc* hypotheses to get it over its difficulties. The ideal is to have no *ad hoc* hypotheses at all. Different people will reach different conclusions as to which system is most convenient; and this is fortunate, since we will then have our scientific theories approached from many viewpoints.

Professor MacMillan desires to postulate Euclidean space and Newtonian time as the basis of all physical science. It must be admitted that a conceptual model of physical phenomena can be built up in this way. There is an unlimited number of thinkable time-spaces or systems of separated times and spaces, and in terms of any of them a conceptual model can be made to fit the facts.

But in physical science we need to choose among

these possible models that one or those which meet an additional requirement. Any model suitable to be retained must be centered around concepts whose agreement or disagreement with facts can be ascertained by experiment or observation.

Now in the universe of phenomena there are such things as natural clocks showing the rate at which time moves in a given small portion of space-time. Such, for instance, are the atoms of a given structure situated in different parts of space-time. These determine local time at all places where they are found. These local times are the real times. It is a matter of observation to find out the relations among the relative rates of these various clocks. To talk about their absolute rate is meaningless, but their relative rates may be found by observation. In this way it is seen that they move at different rates in the sense that such a clock on the sun, for instance, will appear to move more slowly than one on the earth if it is examined by an observer from the earth. This is the meaning of the shift in spectral lines.

Now Newtonian time does not run in this way. It is therefore not the time actually observed in physical science. Moreover, Newtonian time postulates an absolute separation of space and time, whereas in all our experiences they are so intimately conjoined and entangled that we can not separate them without mutilating them. Thus the facts of physical science enable us to make a choice among the possible conceptual models of space and time and to reject certain of them as not having sufficiently close contact with physical phenomena. In this way nature appears to rule out as

unnatural, but not impossible, the conception of Euclidean space and Newtonian time as the fundamental basis of mechanics. The theory of relativity affords an alternative possibility not subject to this objection. Its space-time seems to be much closer to that which is actually indicated by the phenomena of nature.

Some persons find a difficulty in our refusing to make use of the concept of the ether, and they ask us what moves and in what medium it moves when we say that light is propagated with a certain velocity. In the first place we refuse to employ the concept of an ether because nobody has been able to assign to it a consistent set of properties for bringing it into agreement with the necessary facts. Again, we think that the activity manifested in an event is the fundamental thing and that the insistence upon the notion of some sort of metaphysical stuff like the ether only introduces confusion instead of removing the difficulty. It seems that the ether was invented—you will notice that it was never observed but was invented—in order to give us a noun to be the subject of the verb "to undulate". Let us not translate such necessities of language into the laws of physical phenomena. Let us say that a disturbance moves; and let us say nothing more, for that is all that we observe.

I agree with Professor MacMillan in his insistence upon the need of conserving our intuitions as the basis of our scientific constructs. But I believe that he has partly confused the intuitional and the familiar. Some persons are more comfortable in the presence of Euclidian geometry than with non-Euclidian. But I believe that this is a matter of familiar-

ity, and not a matter of the fundamental intuitions of the human spirit. At first the Einstein theory is puzzling. As it becomes more familiar it seems to fit our intuitions better. It appears to me that it will ultimately become more intuitionally comfortable than any other theory so far proposed.

It is easy to mistake that which is familiar to our own generation as the thing which conforms precisely to the fundamental intuitions of the human race. When this error is avoided and the question of what is intuitional is reduced to a proper analysis and we have had time to become sufficiently familiar with both points of view, we shall find, I believe, that our intuitions are in favor of the relativistic interpretation of space-time.

We feel justified in repeating the claim which we made last night and in recalling to your minds a promise which we believe we have kept. There is no experimental fact, tested and corroborated, which is clearly known to be in contradiction with relativity. There are facts which have not been brought under its domain; we have freely admitted that the theory is not ultimate and complete. There are facts which have been erroneously thought to be in contradiction with it; and there are some about which we do not know what to say at present for lack of sufficient evidence or analysis. So far as time has permitted we have done, as promised, one of four things for every presented fact thought to be in contradiction with relativity: We have undertaken to show that the charge of contradiction has not been convincingly supported: or we have repelled the charge with convincing evidence; or

we have shown that the facts alleged do not come within the domain of the present relativity physics; or we have analyzed the reasons why the matter should still be left in the form of an open question. In no case have we had to allow the established validity of the charge, though our weakness has sometimes left us unable to refute it as forcefully as we would have wished. We have not been confronted with arguments of such cogency as to cause us to retreat; perhaps we are not in the right frame of mind during a debate to retreat even from an error. But we have tried to be open to the truth, and we are still convinced that the great preponderance of evidence is in favor of the theory of relativity.

As we draw near to the end of this debate we may assert with emphasis and with confidence, I believe, that the attack has left the stronghold of relativity unshaken. The theory is not perfect; it is not ultimate. It proceeds in the right direction and its principles and conclusions must be wrought into every future system of scientific theory. Changes will be required to adapt it further to the facts of observation and experiment. It is a growing doctrine, and hence must share the characteristics of developing theories. But there is no reason to think that we shall ever go back to the old ways of thinking.

Its fundamental requirement that only observable phenomena shall enter into the laws of physical science is certain to be met by every enduring theory. Since it is only relative motions and relative accelerations that can be observed, the demand of the old dynamics for a distinction between relative and abso-

lute accelerations must be given up in favor of the empirically apparent. "The general theory of relativity is probably the greatest synthetic achievement of the human intellect up to the present time." It has gained adherents among the keenest intellects of the generation in a way which is truly remarkable. It involves much philosophical doctrine, though it is not based on this but upon the search for a deep-lying comprehension of observed facts. It calls clearly for the abandonment of metaphysical assumptions in favor of conclusions based upon the observable differences in phenomena.

Perhaps its most fundamental insistence upon the adherence to observed facts lies in its doctrine of the unification of space and time into the one four-dimensional manifold of space-time. Our conception of this is doubtless subject to change, but there appears to be no likelihood that we will again separate them, since there is no basis in experience for doing so.

The theory meets, so far as we can properly judge at present, all the demands of the supreme test of adequacy in the case of the phenomena to which it applies. It is a more convenient theory than any of its rivals, since it succeeds far better than they in dispensing with *ad hoc* hypotheses; it has esthetic qualities suitable to recommend it to the most fastidious human spirit, once it has become sufficiently familiar to allow unreasoned prejudice against it to disappear, and it stands alone in the measure of its success in accounting in a fundamental way for the facts of observation and experience. The contemplation of its beauty and elegance and the simplicity of its foundations and its

good success among the phenomena of experience is enough to produce in one the afflatus of prophecy and to inspire in him a confidence in its enduring qualities akin to our certainty of the unchangeableness of the past. If I were not confronted with the actual existence of living human beings witnessing to the contrary, I would be unable to see how any one properly acquainted with the theory could fail to be moved with a profound confidence that it is an advance looking in the direction which future human thought will take.

Before concluding I wish to speak of the bearing which relativity has on the general basis of philosophical thought and on the problem of ethical values.

The theory of relativity has brought us to a new analysis of the meaning of the customary abstractions employed in scientific thought and to a new appreciation of their respective roles and their interactions. It has helped us to see and to realize the implications of the fact that all abstractions have been developed from an intuitive phase and that they are subject to the limitations imposed upon them by their origin. They can never have a greater validity than the intuitions from which they have sprung, and they must be subject to constant revision and extension from the influence of the intuitions which underlie them. The intuitions back of scientific thought are more fundamental than the abstractions by means of which that thought takes explicit and precise form.

You can not fail to see that this conclusion has wide implications in the matter of ethical and religious thought. In these fields it is difficult to get far beyond the intuitions. There has been a tendency to

allow the abstractions of scientific thought to tyrannize over these intuitions. But when we realize that the abstractions of scientific thought must be subject, in the last analysis, to the intuitions underlying science and that these intuitions have the same character as the ethical and religious intuitions, we can no longer consent to have the abstractions of science tyrannize over ethical and religious intuitions. The latter must be allowed as great validity as those which underlie science, and science is under as much obligation to square with them as with its own underlying intuitions. For the same reason science can not be allowed to tyrannize over our social intuitions and the institutions of society which have grown out of them.

In the development and analysis of the theory of relativity, and in comparing it with rival theories, one comes to a clearer understanding of the range of validity of a particular abstraction and its tendency to be included in a larger abstraction which replaces it. In the gradual evolving of codes of conduct we have a like process of extension and inclusion. "Relativity," as Birkhoff says, "does not suggest then that ideals are relative and shifting, but rather that they will enlarge from time to time."

The great variety of ways in which an abstraction can be approached and its multiple relations to the phenomena from which it arises suggest a new view of the nature of thought. We see it no longer as an absolute copy of nature but as a more or less perfect picture of it; sometimes we look upon it even as a cartoon of nature, emphasizing one feature to the point of distortion. Such is the picture of time afforded by

Newton's description of it as eternally flowing evenly independent of space. A realization of this inherent element of distortion in the nature of a scientific abstraction makes for sympathy and tolerance. My neighbor has as much right to distort it in his direction as I have to distort it in mine. Two things are required of us: that we recognize the distortion in our picture, the partaking of the nature of a cartoon; and that we strive to remove it insofar as it conflicts with fact and the demands for esthetic satisfaction and convenience.

The historical development of the theory of relativity, the way in which it has grown out of earlier theories, has helped us toward a freedom to use an abstraction and yet not be enslaved by it. It has made for tolerance, as is perhaps illustrated by the spirit in which this debate has been conducted. In particular, it has struck a blow against the intolerance toward ethical and religious and social intuitions which has characterized a certain group of scientific workers, and it has taken the foundations from under the materialistic philosophy which supported them, as we shall presently show. In so doing it has strengthened the hands of those more profound and more idealistic scientists whose science has always allowed a place for the deeper values of life and conduct. It is one among the many forces now making for a return to the more idealistic conceptions of philosophy, conceptions which had been obscured for a long time by a false view of the nature of abstractions in science.

The theory of relativity appears to me to have swept away the basis of the old materialism in philosophy.

In this it has been ably supported by many other remarkable developments of modern physical science—a science whose achievements in the last thirty years have been the amazement of all intelligent onlookers, a science which now has much to say to all natural sciences about the present outlook and ideals and norms for scientific progress, a science which is destined to hold such a central position in philosophical speculation in the next decades as mathematics held in the past decades.

These influences have swept away the basis of the old materialism in philosophy. "Matter" is now a different thing from the matter on which that doctrine was built. Even the space and the time underlying the old materialistic theory have given away to a new conception of space-time—a conception marking the radical return of thought to the basis of experience. The whole theory of motion has undergone a fundamental change under the influence of relativity. There is a natural limit to the velocity of a material body in a portion of space-time having a given structure. Mass increases with velocity. There is a mutual interchange of mass and energy so that the two are but different aspects of the same thing—a conclusion supported both by relativity and by many other considerations converging to the same end. Time and space are conjoined and are inseparably entangled—a fact that is now to be admitted in thought as well as being found in all experience. The structure of space-time itself is modified by the matter in that space-time and by the motion of that matter. If I wave my hand I change the structure of space-time in my neighborhood.

The former basis of the old materialism is gone and that doctrine is now quite impossible It is absurd to speak of a mechanical explanation of life and thought when we have found ourselves in such difficulties that we no longer know what we should mean by a mechanical explanation of phenomena not involving life.

With no intention or expectation on the part of the founders that it should be so, the theory of relativity has become one of the crusaders for the freedom of the human spirit to follow its deepest and most profound intuitions, and its history has helped to teach us that science has nothing which can be properly opposed to such a freedom. The theory of relativity has done much to loosen the shackles of the human spirit; and, in so doing, it has helped to open the way for a new evaluation of science and life and thought and a new understanding of their meaning.

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